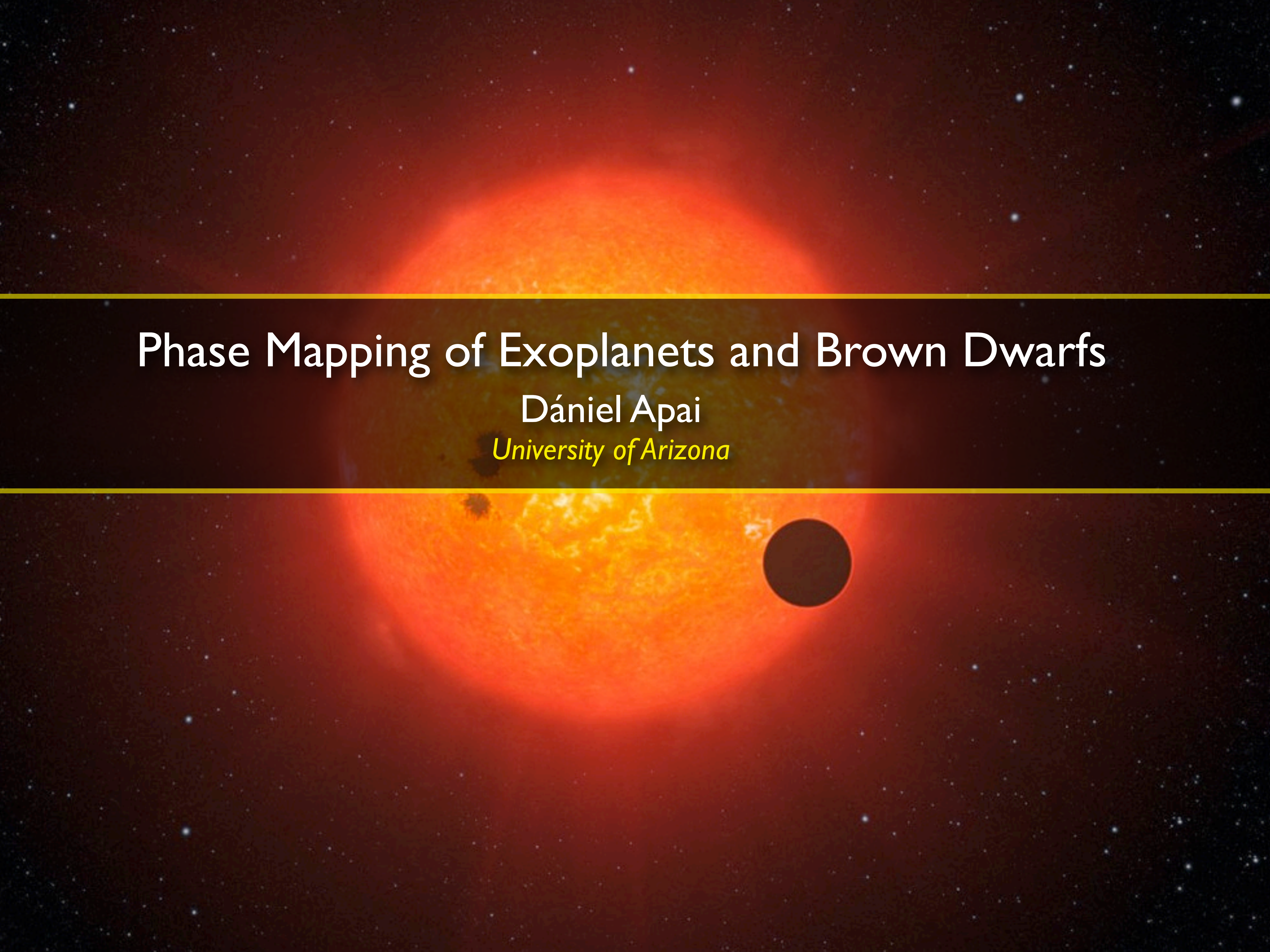
Phase Mapping of Exoplanets and Brown Dwarfs

Dániel Apai
University of Arizona



Exoplanets and Brown Dwarfs

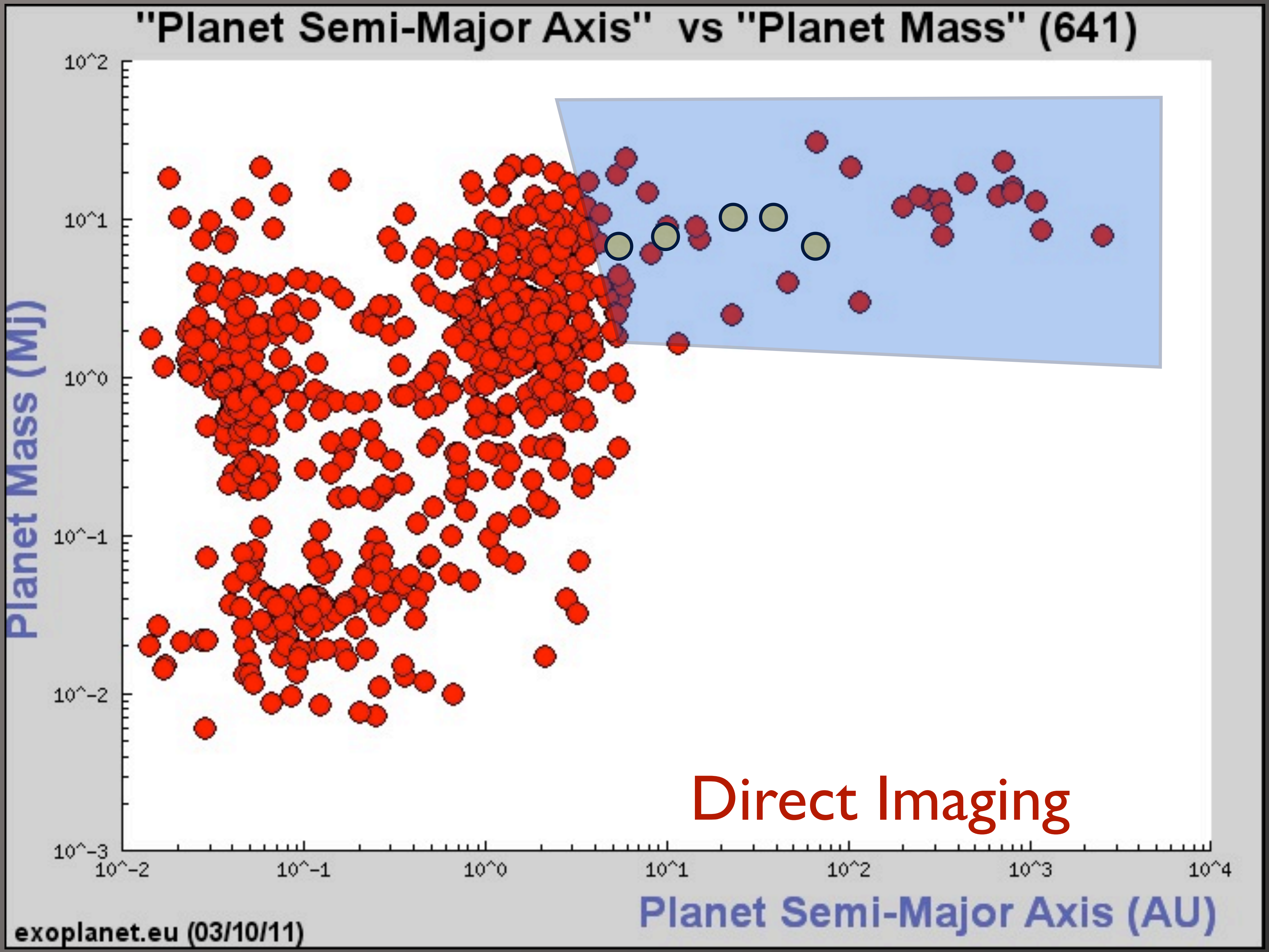
Exciting, new, and challenging objects for astrophysics

Goals: Physical, chemical properties and formation of planets all the way down to Earth-like planets

Physical Characterization:
Planet Frequency and semi-major axis distributions
Mass
Radius

Exoplanetary Atmospheres:
Pressure-Temperature profile
Chemistry: Elemental and Molecular Abundances
Clouds/Condensation

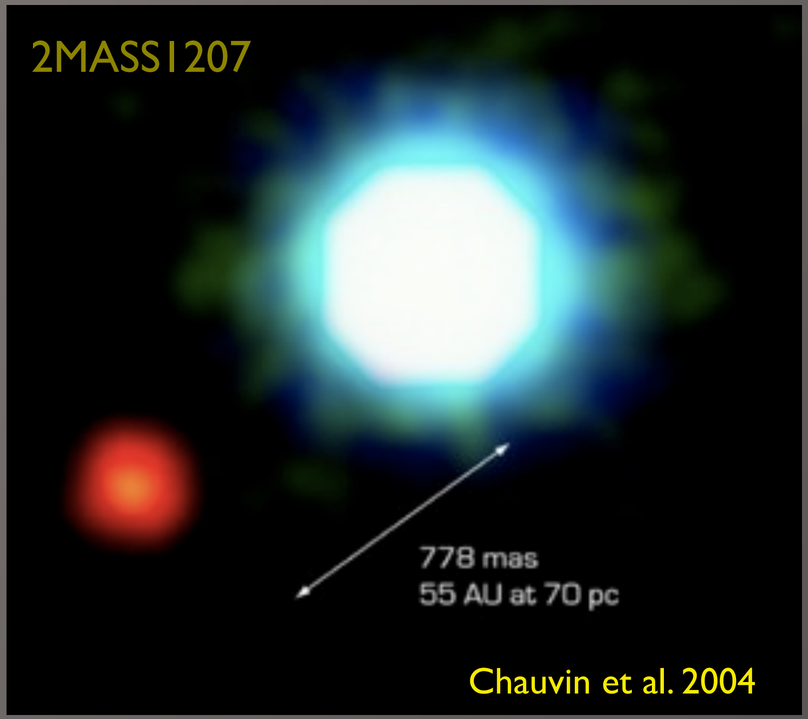
One-dimensional models are not enough!



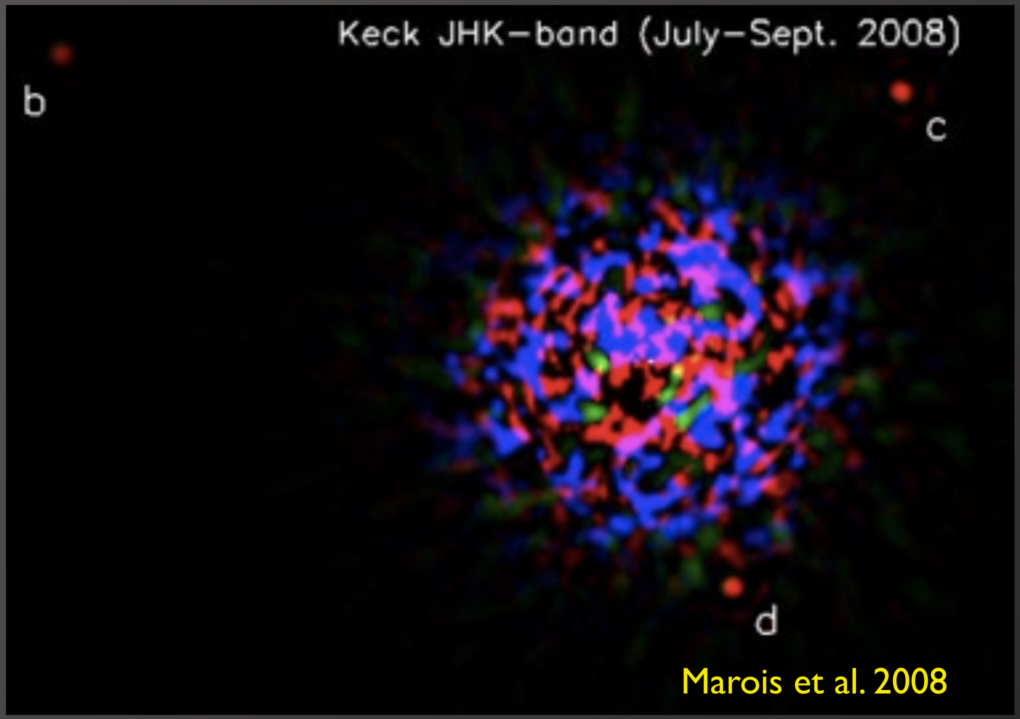
Heavily Irradiated

Weakly Irradiated Planets
Giant Planets: Energy from Gravitational Contraction

Directly Imaged Planets are Weakly Irradiated



Chauvin et al. 2004

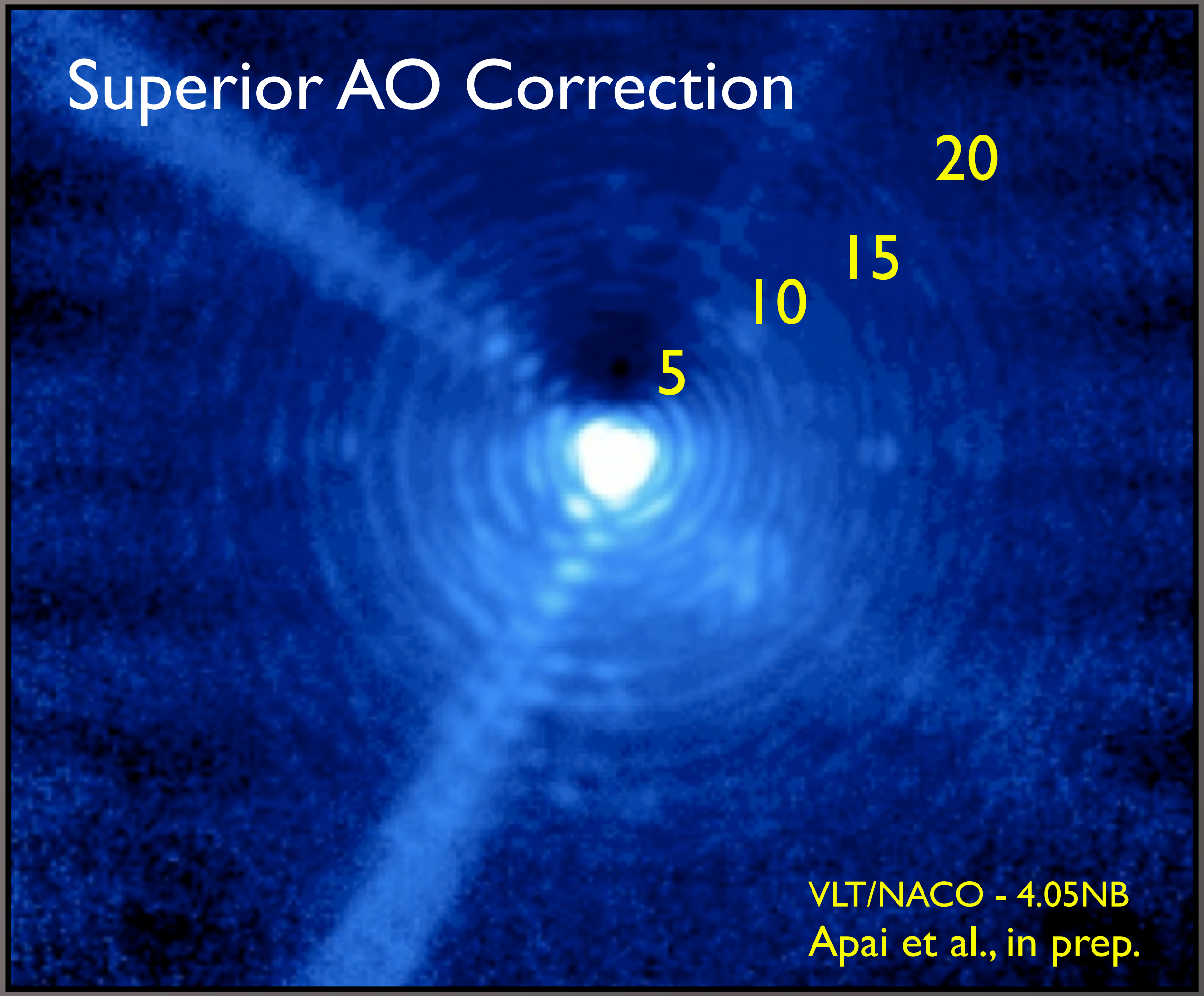


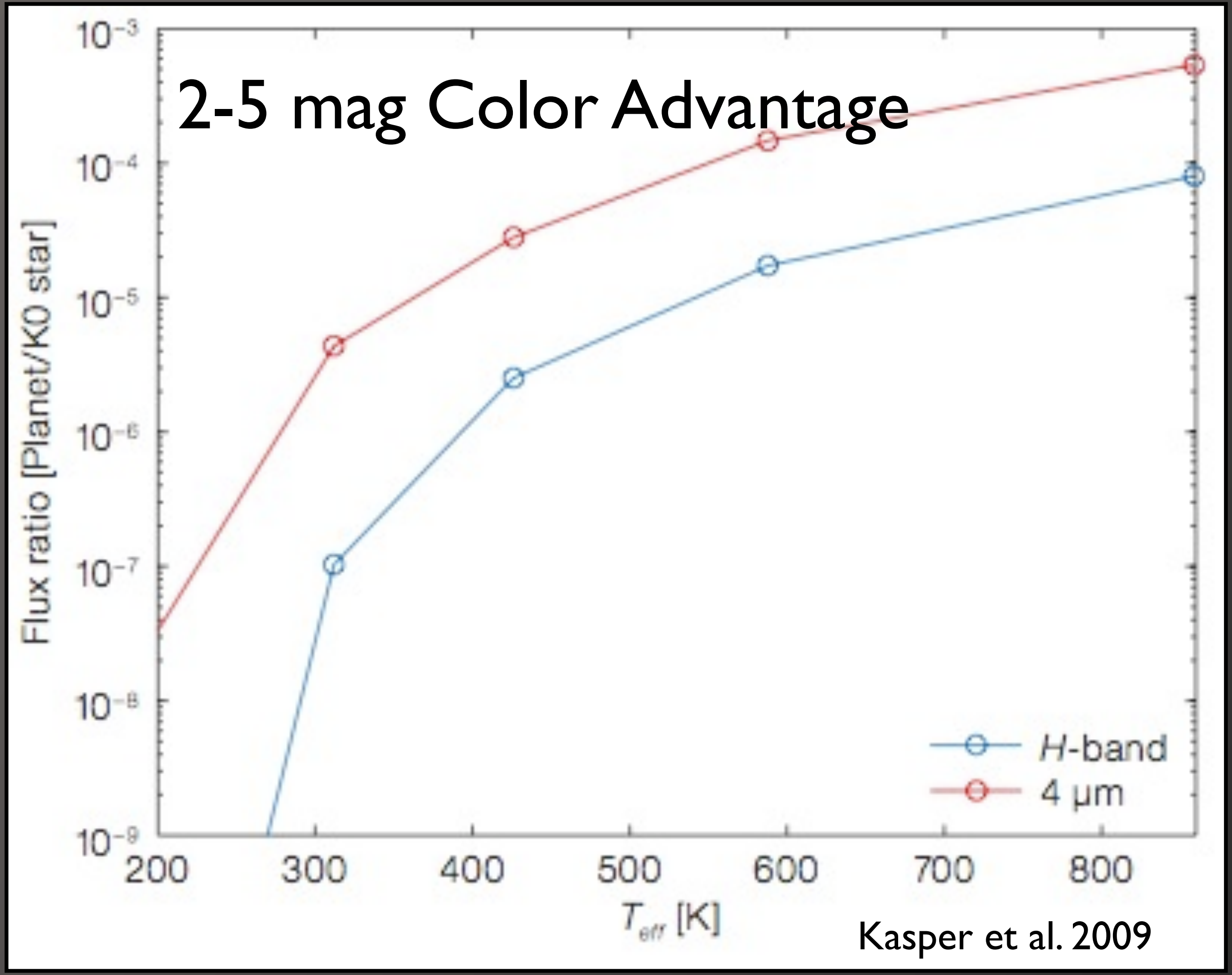
Marois et al. 2008

Pushing the Boundaries of High Contrast Imaging

3-5 micron Angular Differential Imaging

Demonstrated on VLT (Kasper, Apai et al. 2007) and on the MMT (Hinz et al. 2008)





This technique was used to detect the two most challenging directly imaged planets yet.

High-Contrast Imaging Surveys

D. Apai, M. Kasper, P. Hinz, M. Meyer, V. Kostov, M. Janson, I. Baraffe, Lagrange and AO teams

New High-Contrast Imaging Techniques on VLT and MMT

>160 Stars Observed in Four Surveys (PIs: Apai, Kasper)

Works at 3-5 μm, Strehl~90%, 2-5 mag gain

Sun-like stars with truncated debris disks (Apai et al. 2008)
Young sun-like stars (Kasper, Apai et al. 2007, 2010)
Volume-limited survey <6pc (Apai et al. in prep).
Young AF-type stars

Total of 14 MMT nights, ~25 VLT nights

Giant Planet Population around Sun-like Stars

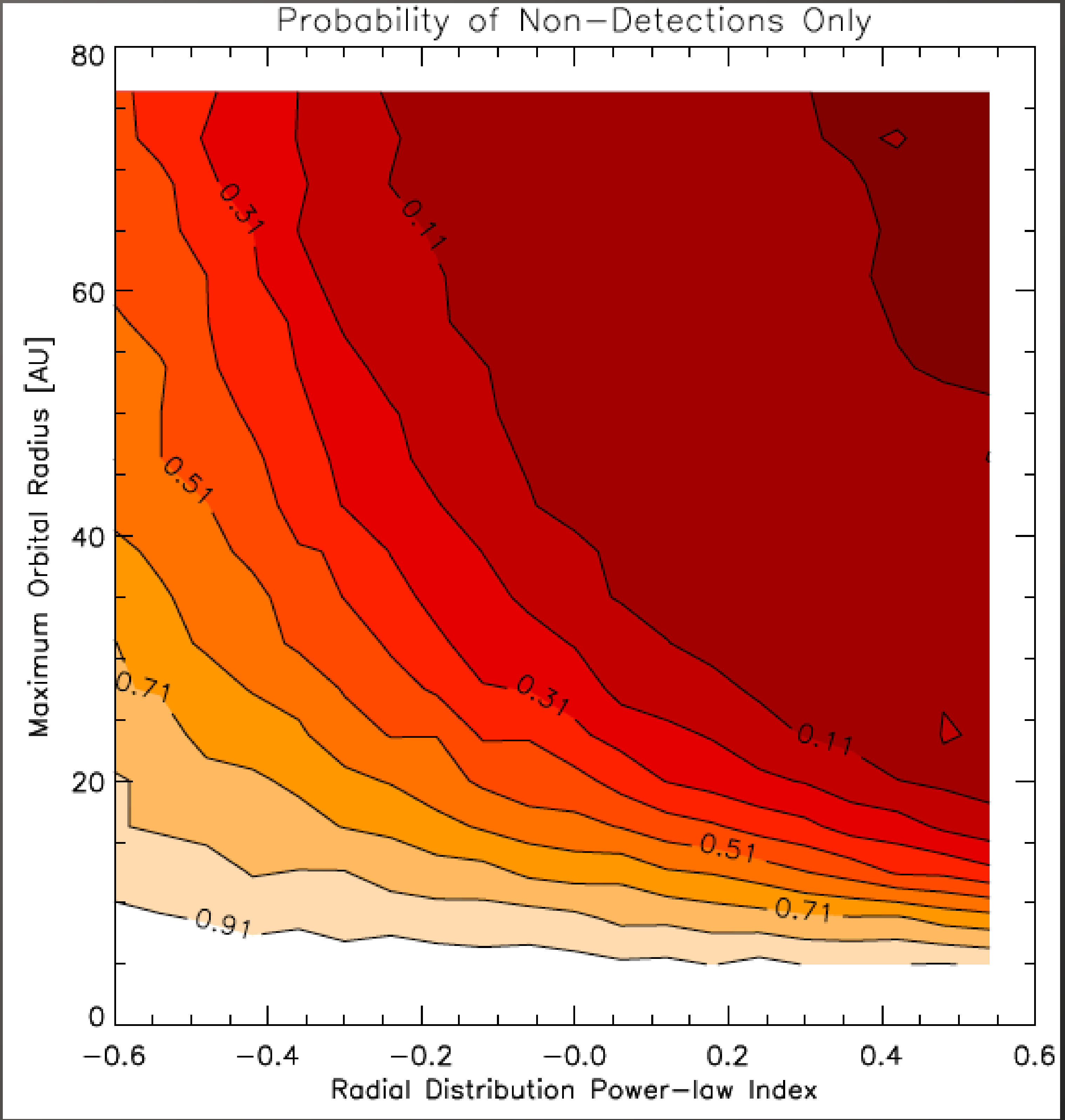
Orbital Radius Distributions:

$P(a) \sim a^{\alpha}$
5 AU < Rmax < 75 AU

RV Giant Planet Population confined to a<30 AU at 90% confidence level

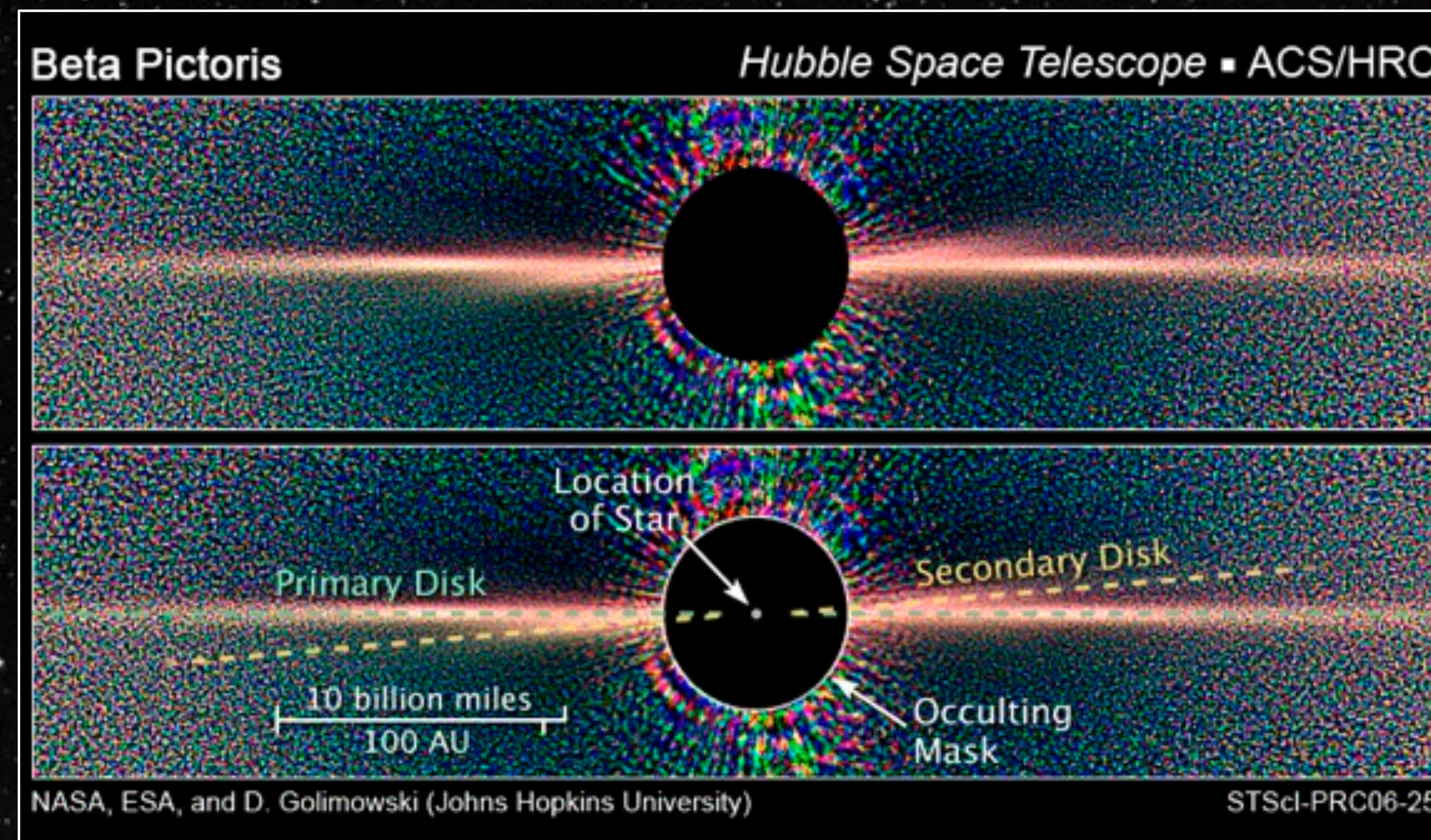
Kasper, Apai et al. 2007 A&A 472, 321
Lafreniere et al. 2007; Nielsen et al. 2008;

Kasper, Apai et al. 2010 - A-stars
Janson, Apai et al. 2009 - eps Indi A



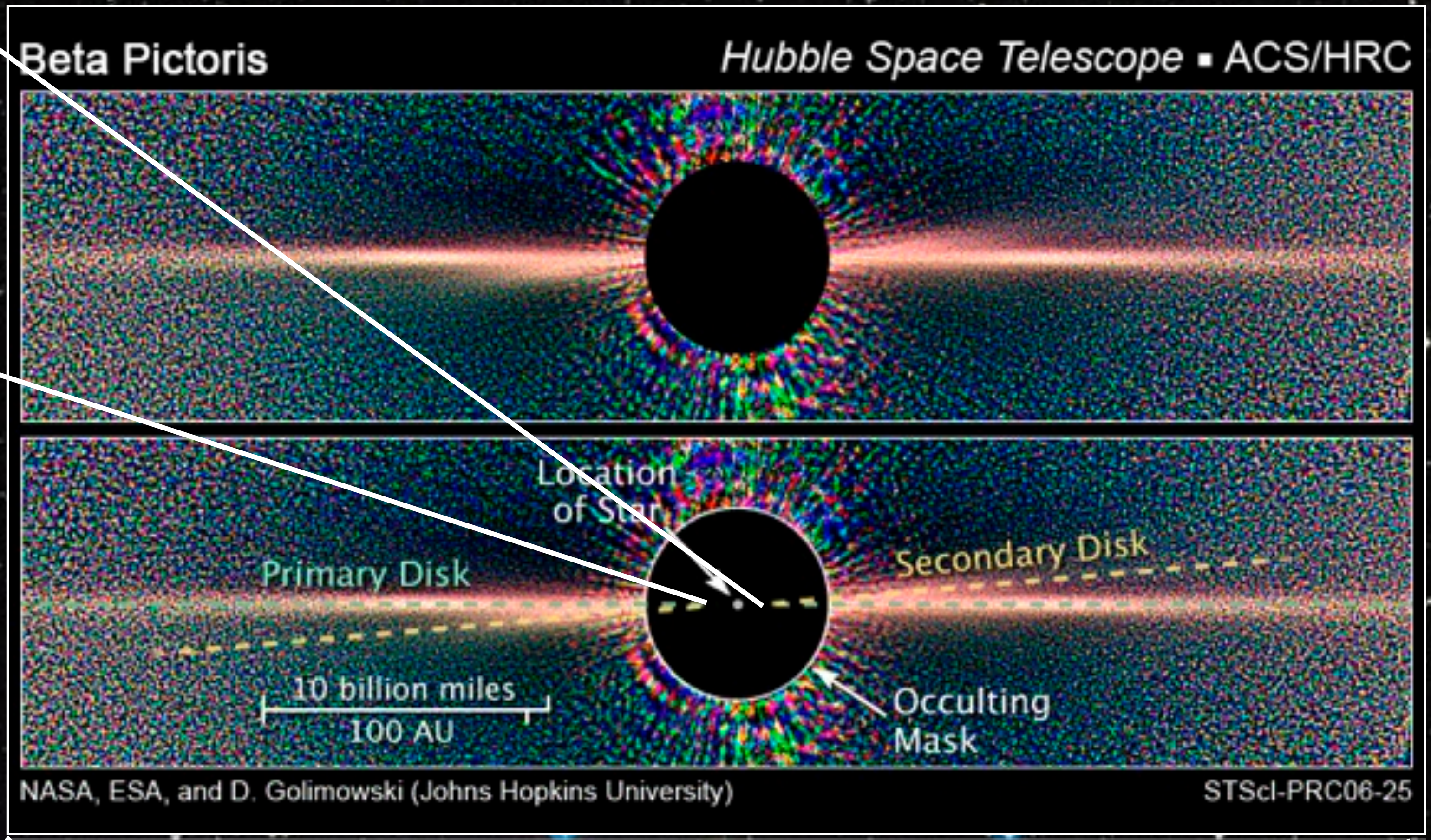
β Pic b

β Pic b


Beta Pictoris
Hubble Space Telescope ▪ ACS/HRC
Location of Star
Primary Disk
Secondary Disk
10 billion miles
100 AU
Occulting Mask
NASA, ESA, and D. Golimowski (Johns Hopkins University)
STScI-PRC06-25

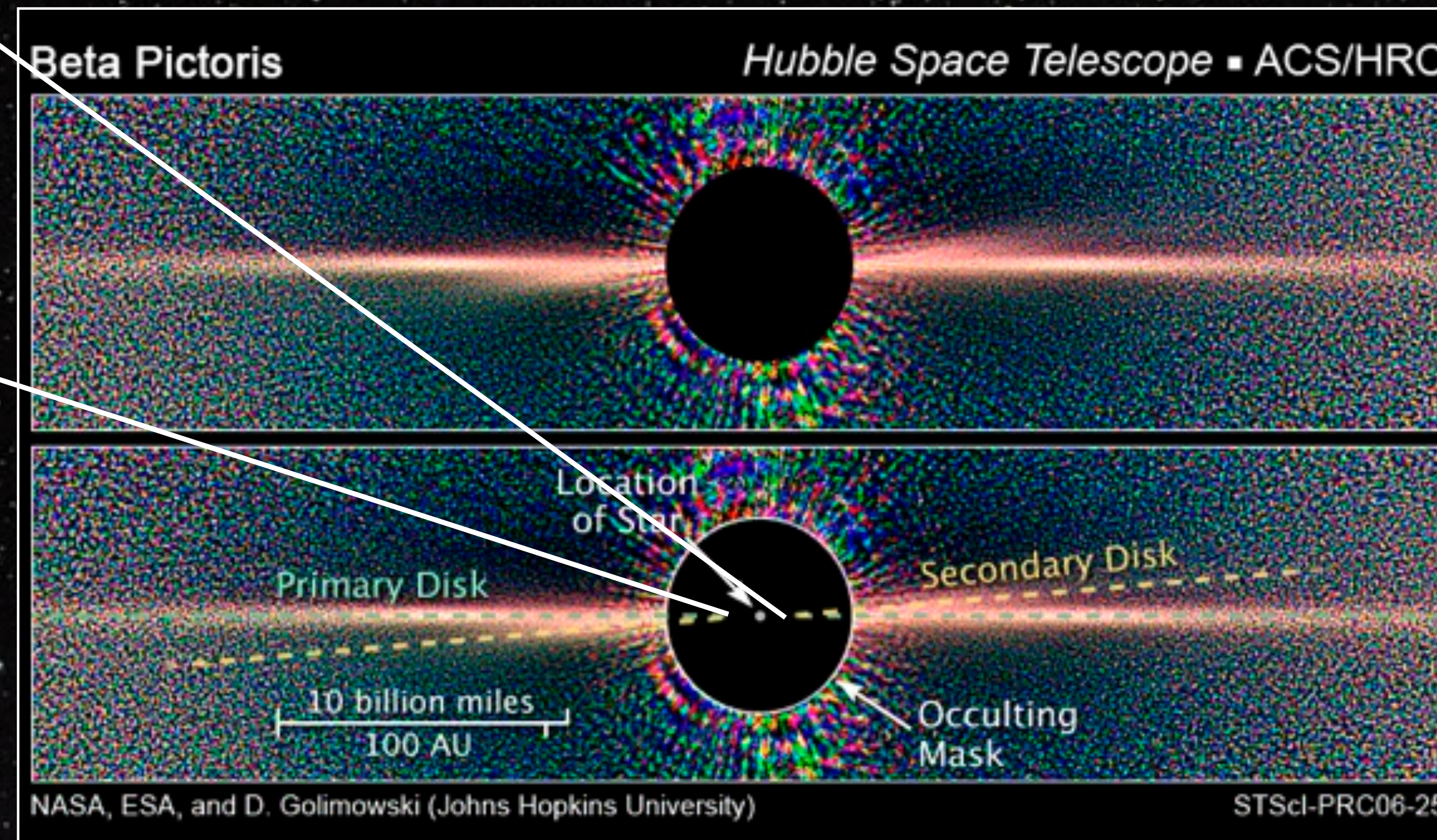
β Pic b


2003


Beta Pictoris
Hubble Space Telescope ▪ ACS/HRC
Location of Star
Primary Disk
Secondary Disk
10 billion miles
100 AU
Occulting Mask
NASA, ESA, and D. Golimowski (Johns Hopkins University)
STScI-PRC06-25

β Pic b


2009
N
E
400mas


Beta Pictoris
Hubble Space Telescope ▪ ACS/HRC
Location of Star
Primary Disk
Secondary Disk
10 billion miles
100 AU
Occulting Mask
NASA, ESA, and D. Golimowski (Johns Hopkins University)
STScI-PRC06-25

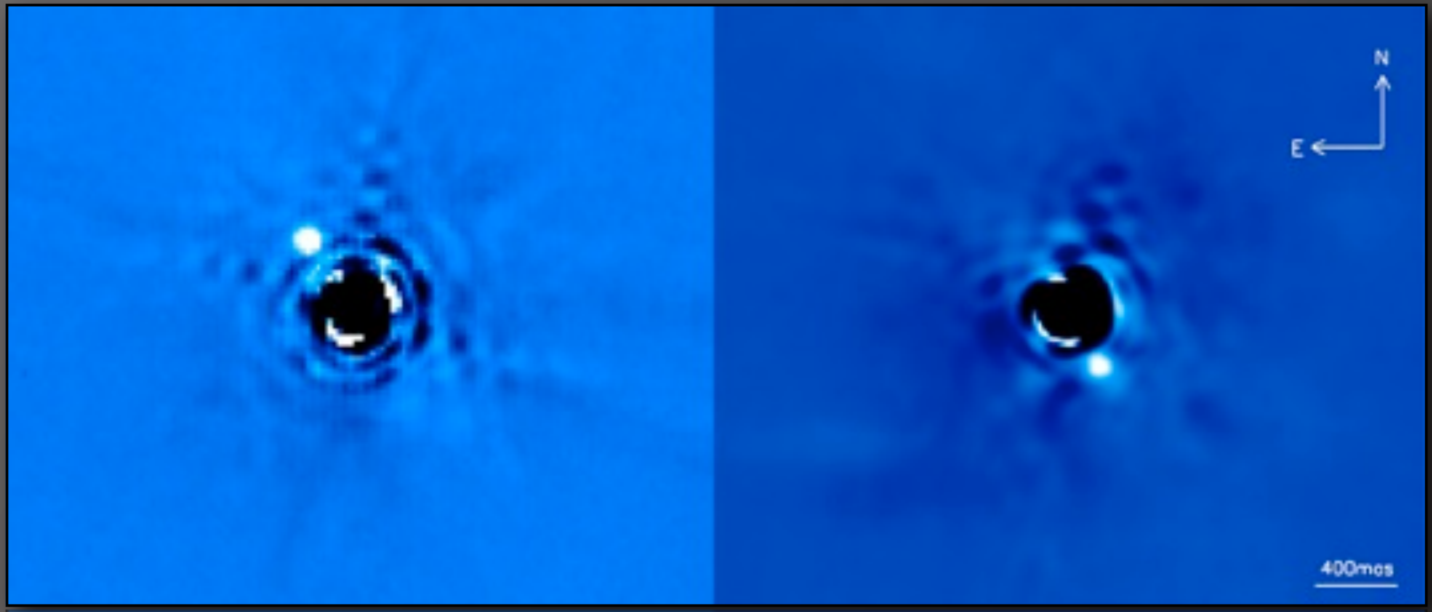
β Pic b

First planet imaged on scales of the Solar System
(a~8 AU, P~12–17 yr)

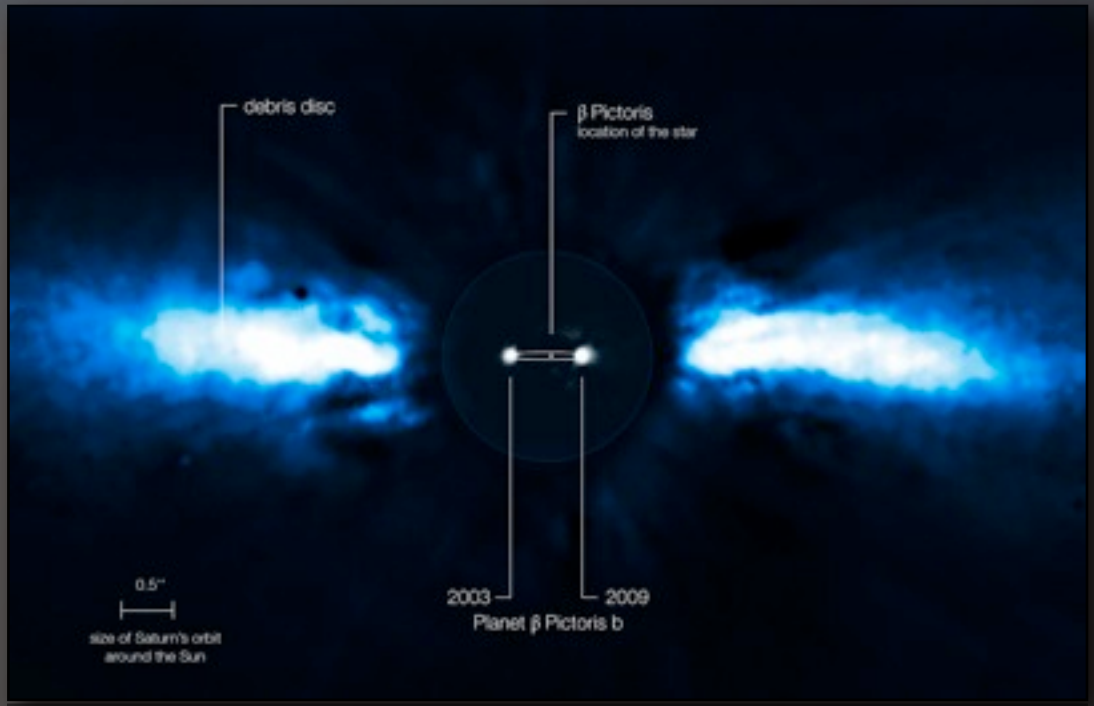
One of the Youngest Planets Directly Detected
($12^{+8,-4}$ Myr)

First Planet Imaged inside a well-studied, imaged disk

HST/STIS program monitoring the changes of the disk as the planet orbits in it
PI: Apai



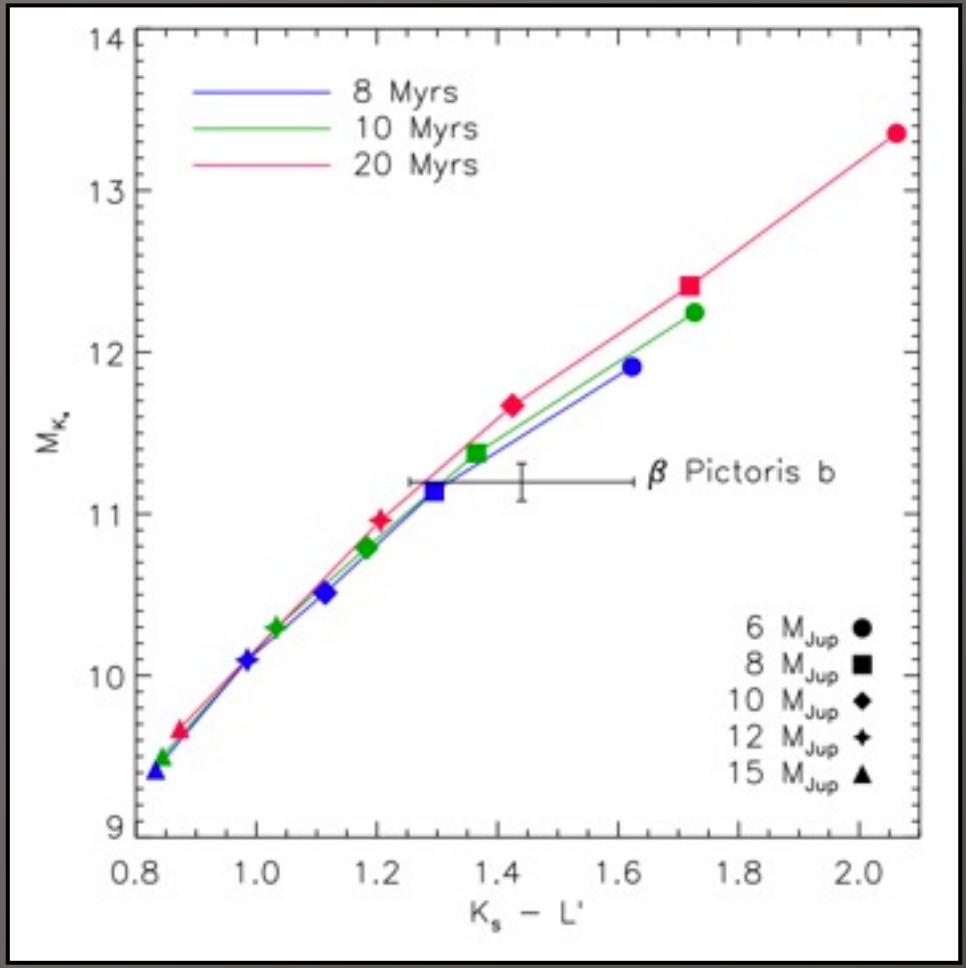
Lagrange et al. 2010 Science



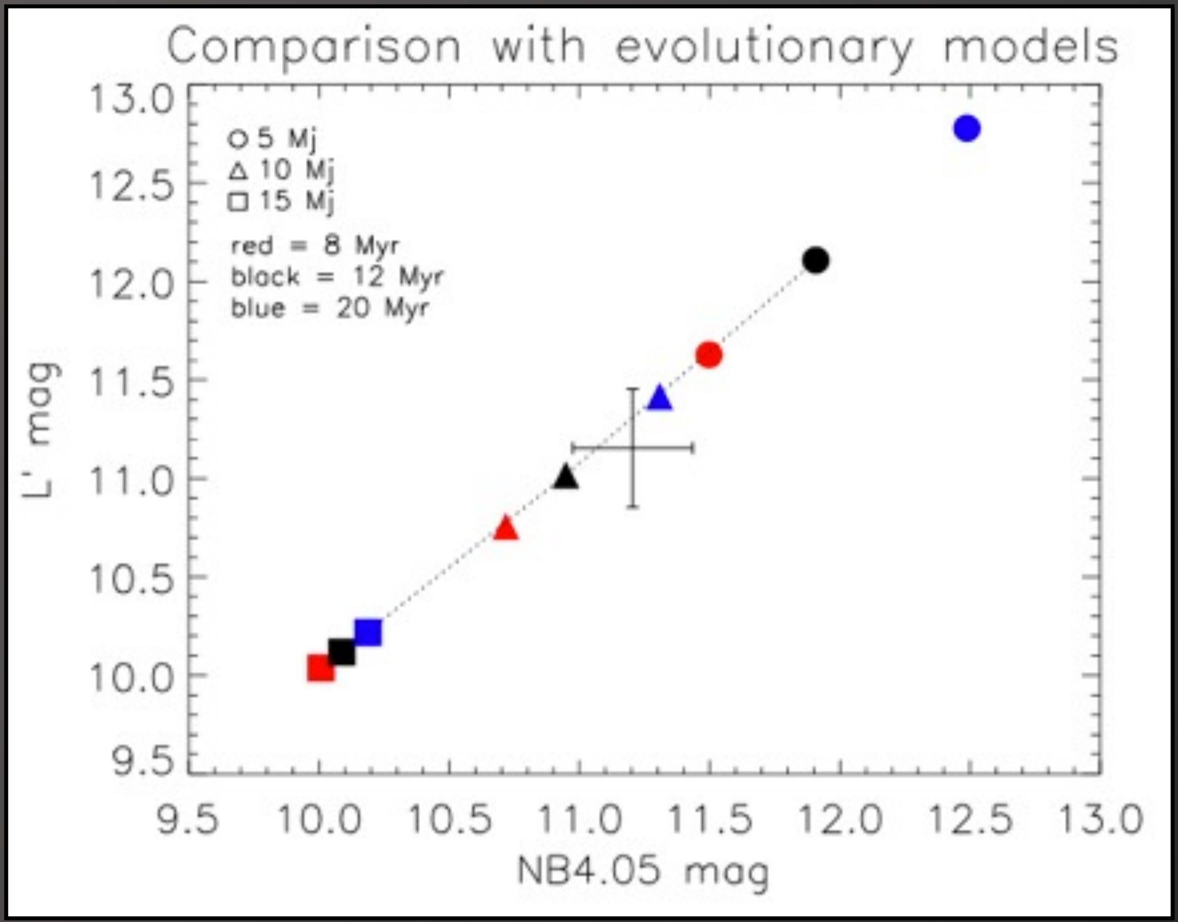
β Pic b

Young Planet with well-characterized age

β Pictoris b: Ks, L', 4.09nb
Quanz et al. 2010: L' - NB4.05 color matches L4 BDs (T~1,500-1,700 K)
Bonnefoy et al. 2011: Model comparison 1,700 K +/- 300 K
Good fits to models, but b is redder than models predict

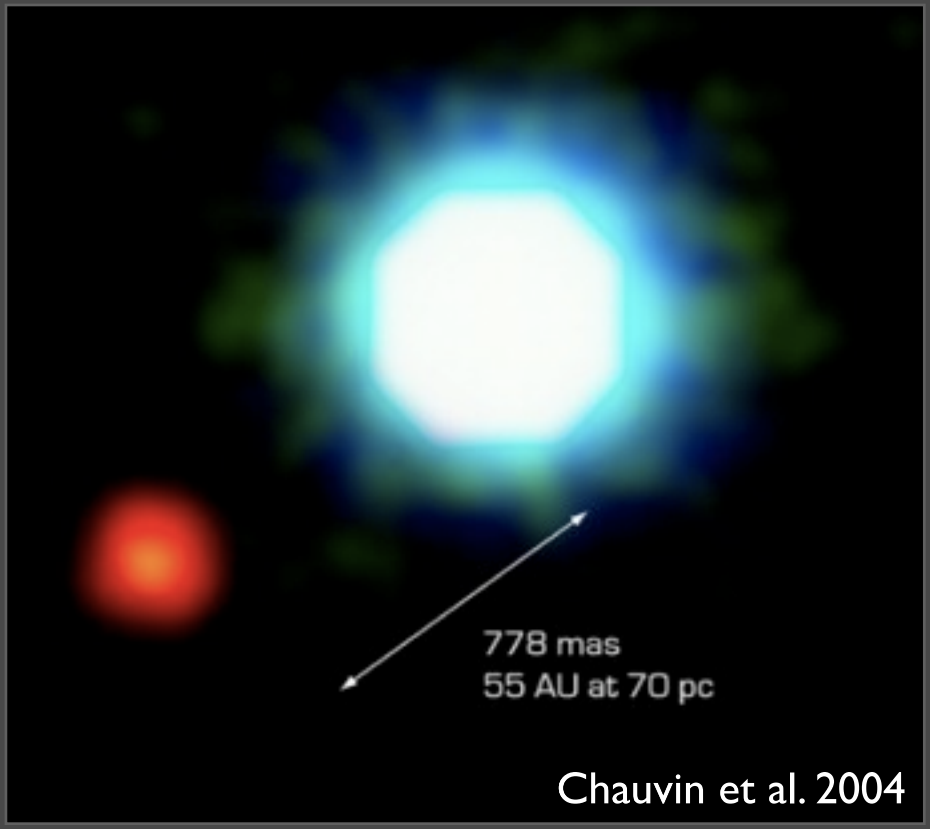


Quanz et al. 2010 ApJ



Bonnefoy et al. 2011

2MASS 1207b



Chauvin et al. 2004

Chauvin et al. 2004, 2005

7 M_{Jup} companion to a ~25 M_{Jup} BD

analogue to ~L5 type BD

Spectra is well explained with T_{eff}~1,600 K
(Patience et al. 2010), but source is under-luminous by a factor of 10!

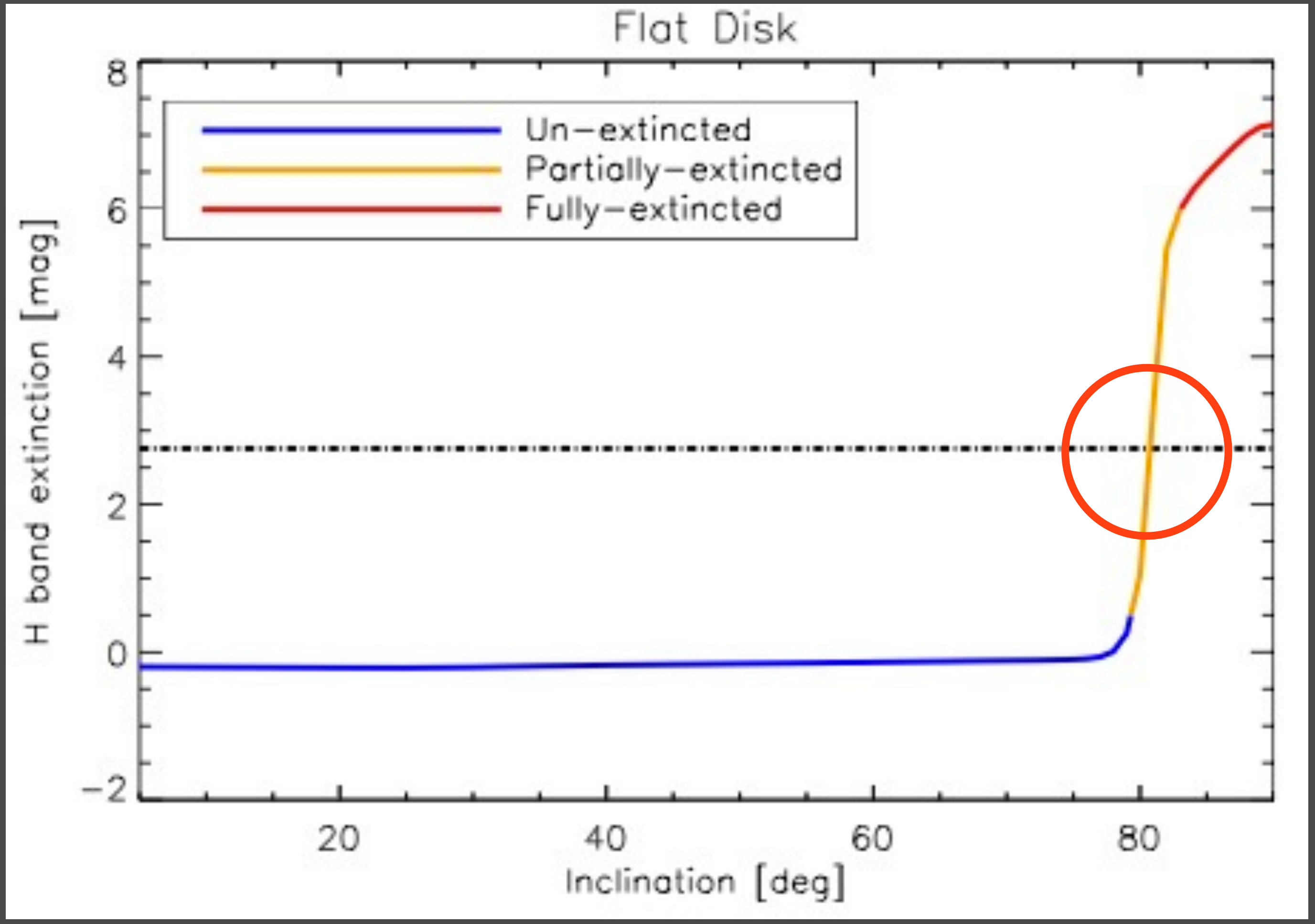
Sterzik, Pascucci, Apai et al. 2004 A&A: 1207A has a Disk

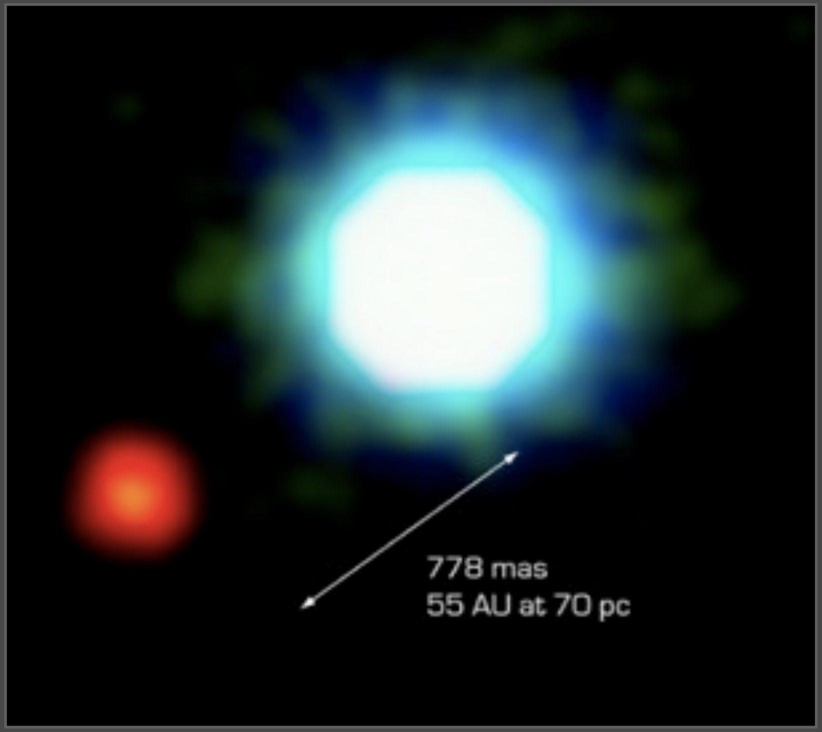
Mohanty et al. 2006:
Edge-on Disk is Occulting 2M1207b and introducing gray extinction!

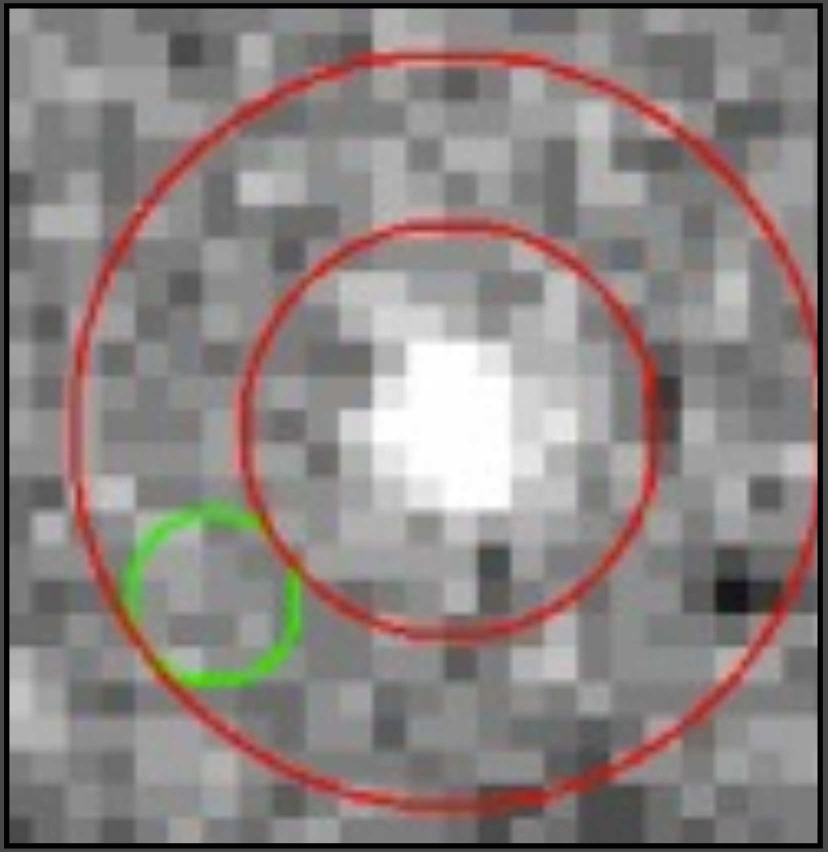
2M 1207b

Skemer et al. 2011 ApJ

Deep Gemini/TReCS imaging reveals no excess at the position of b at a a level of <0.92 mJy at 3 σ





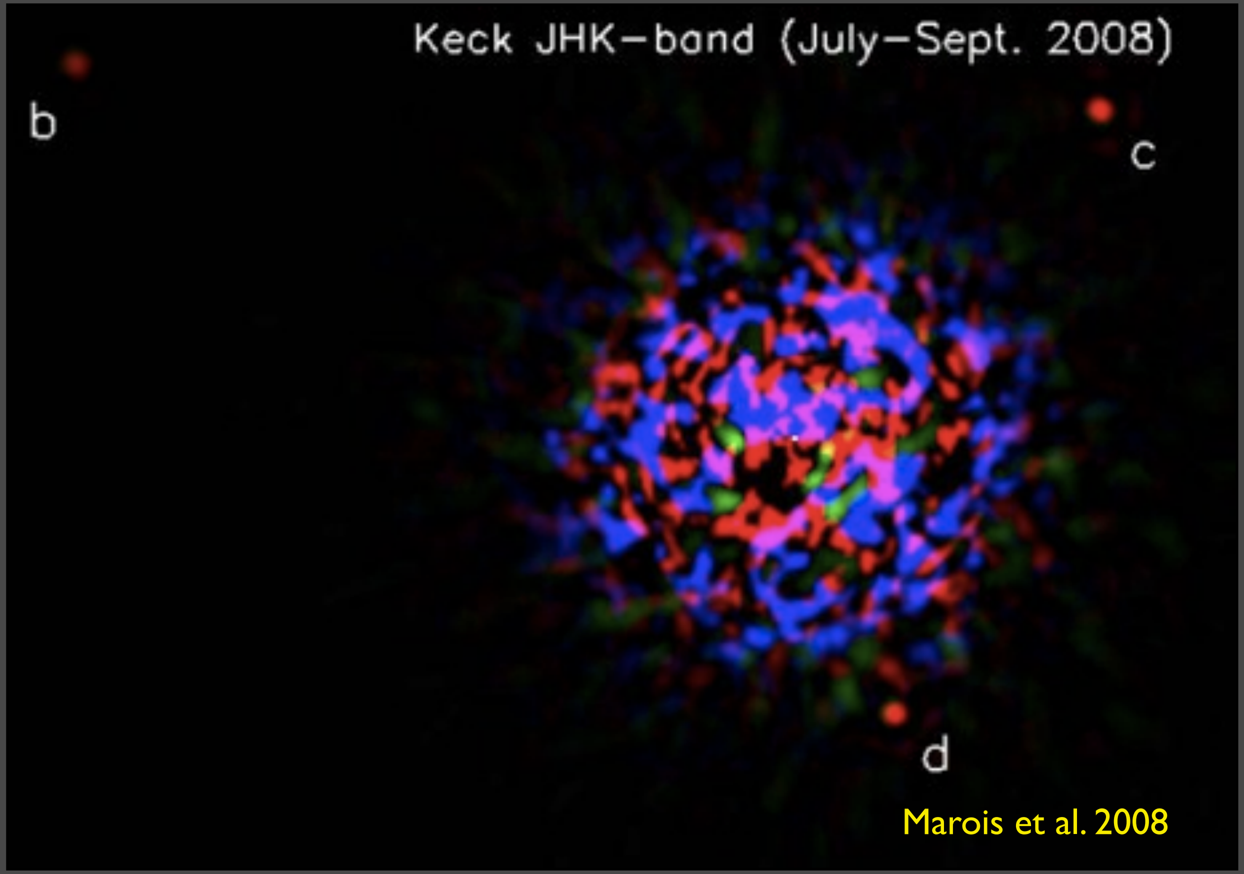


Disk is exceedingly unlikely

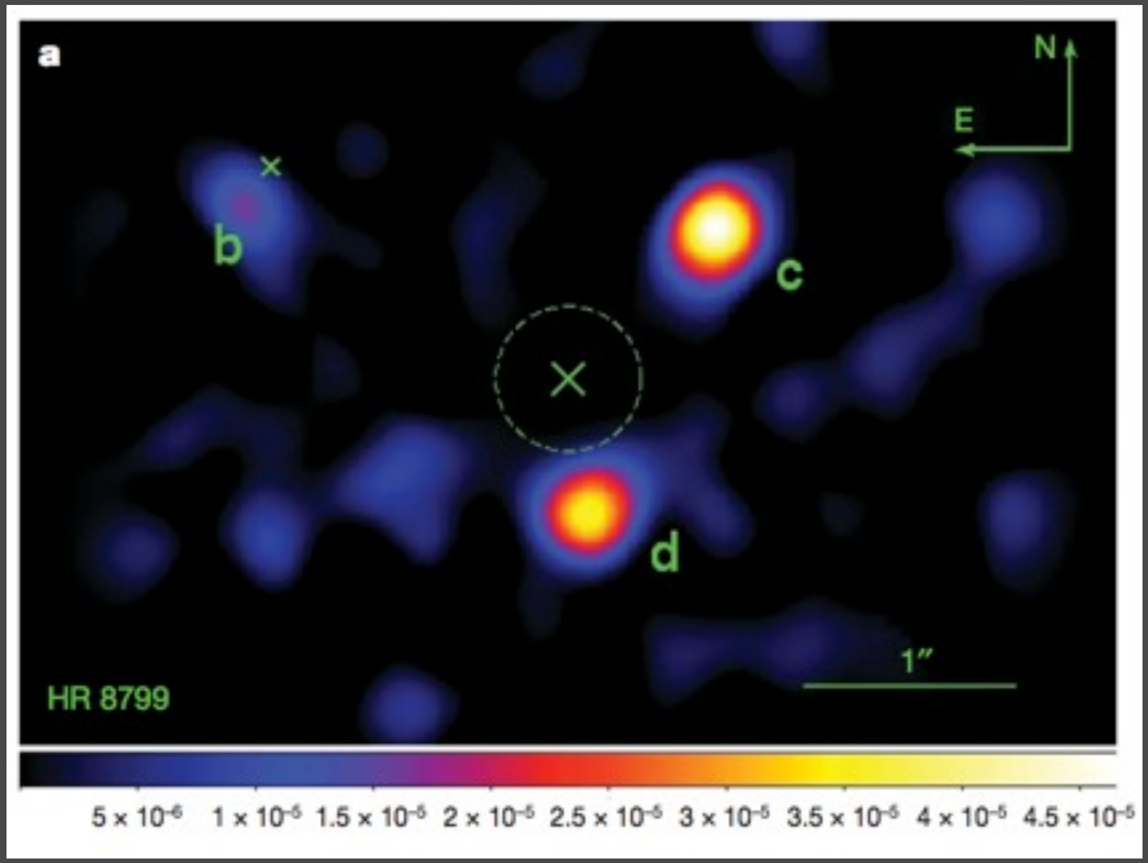
Instead: models with much thicker clouds may work

HR 8799 bcd

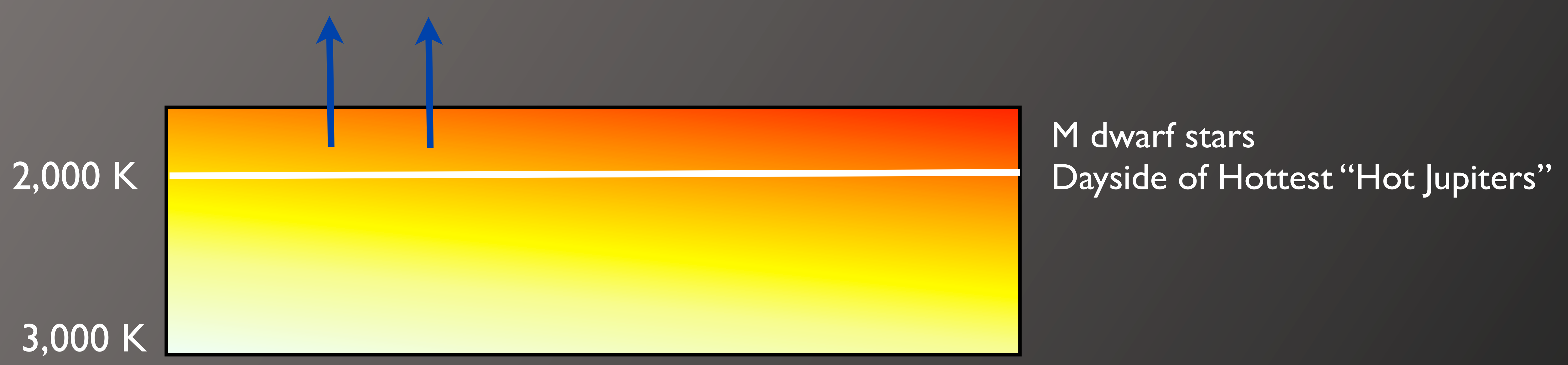
Discovered in 2008 with Keck/Gemini
b, c, d ~10 MJup and ~ 1,000 K
b is also significantly underluminous

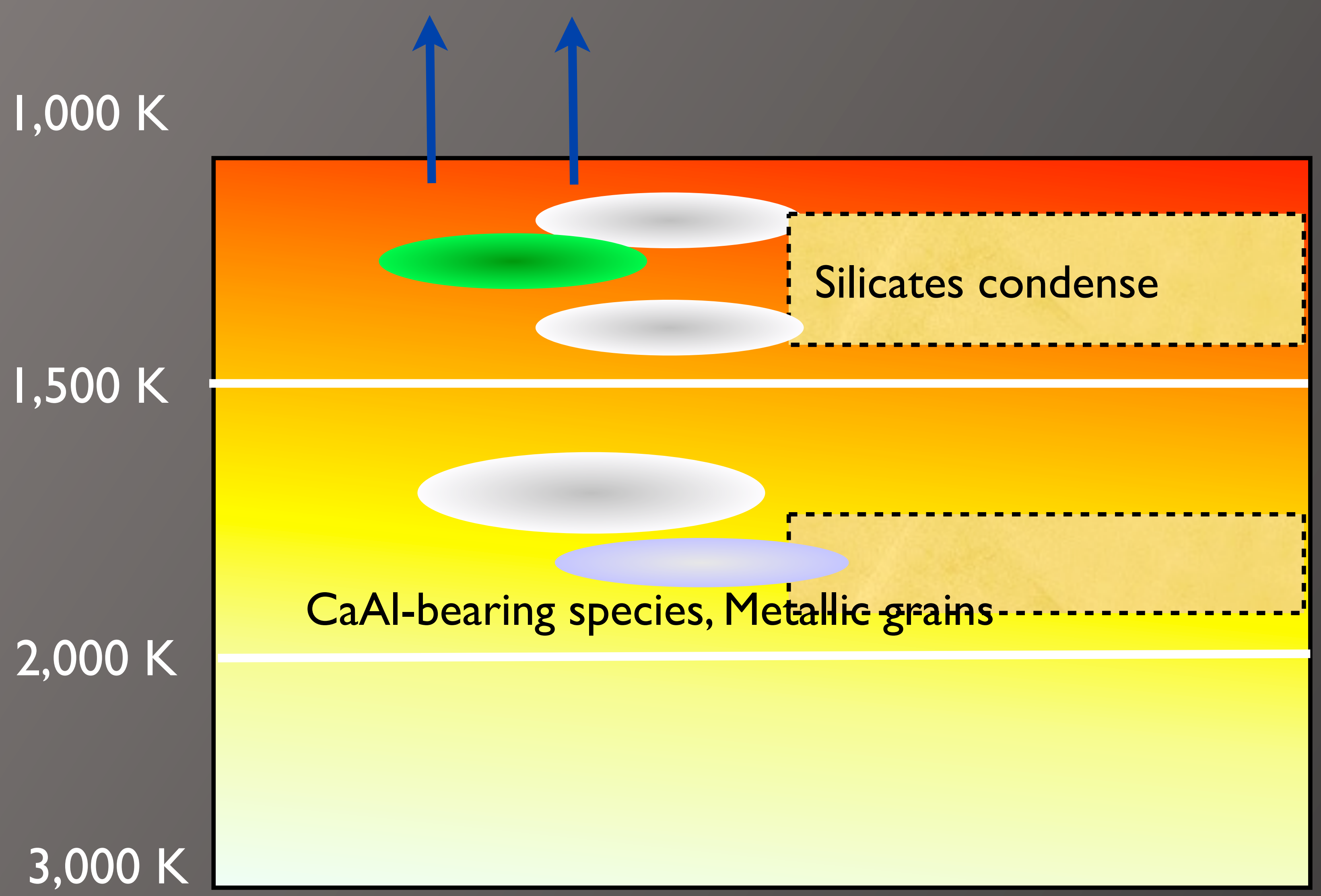


Marois et al. 2008

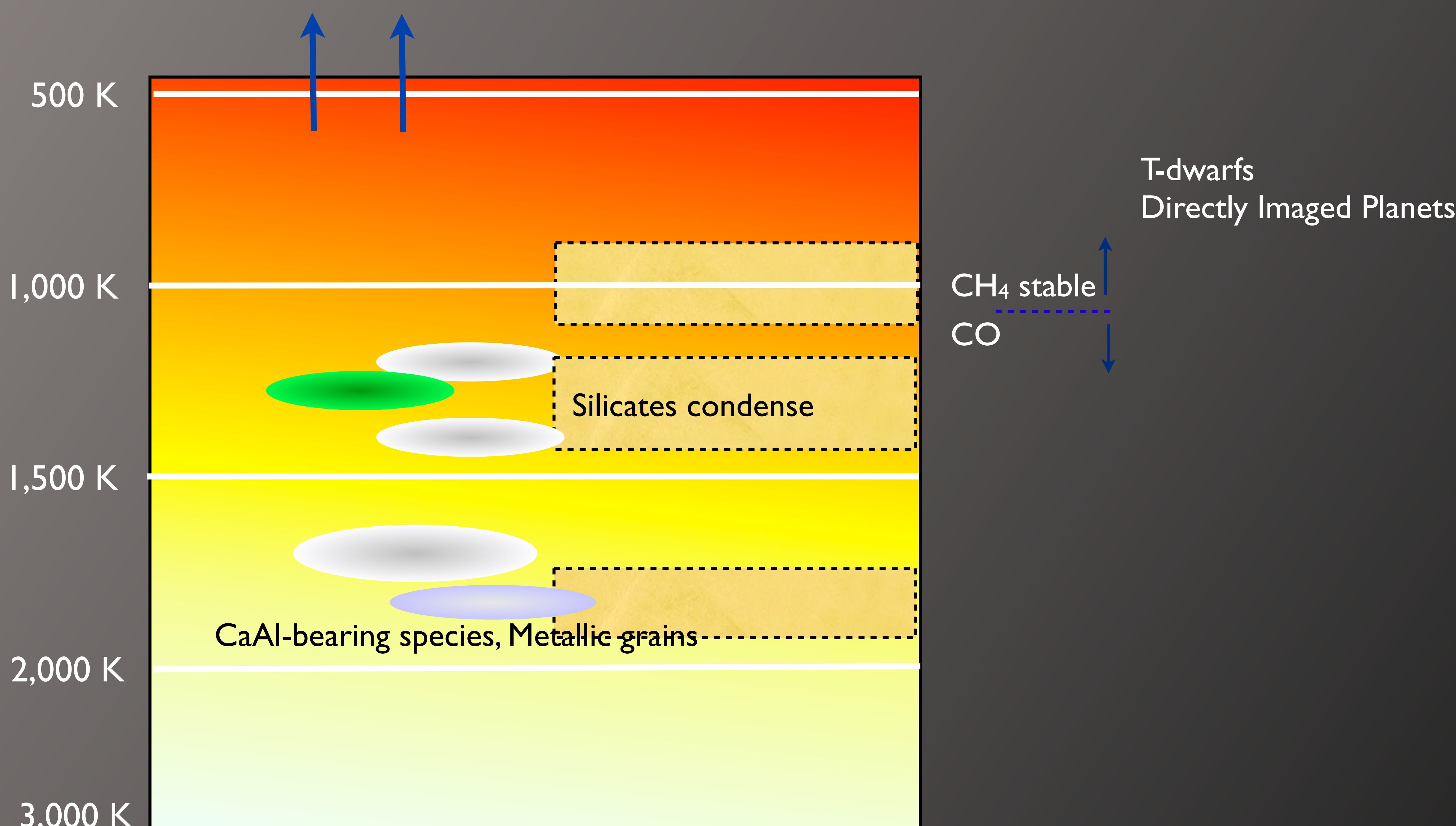


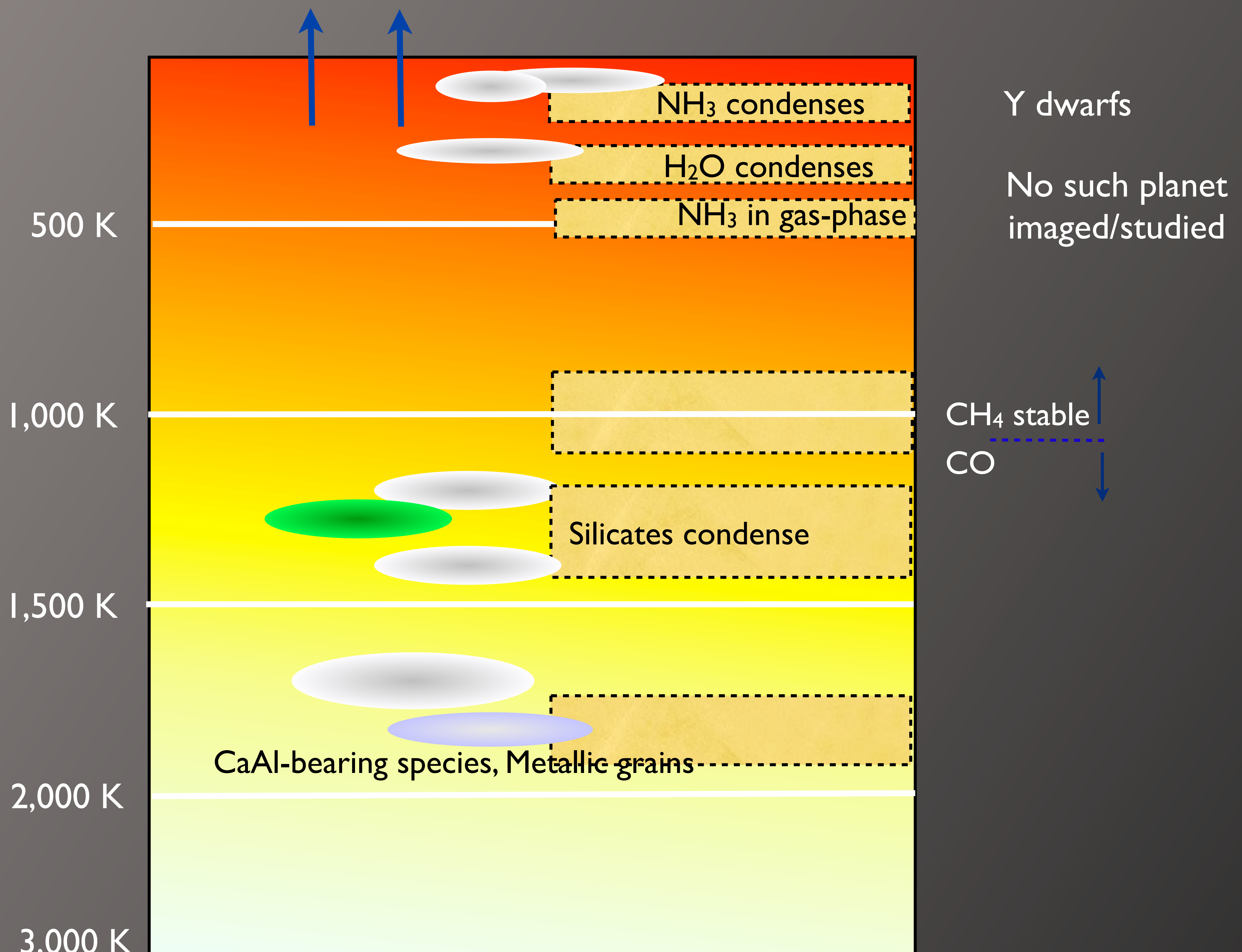
Serabyn, Mawet & Buruss 2010
Palomar 1.5m + vortex coronagraph


2,000 K
3,000 K
M dwarf stars
Dayside of Hottest "Hot Jupiters"

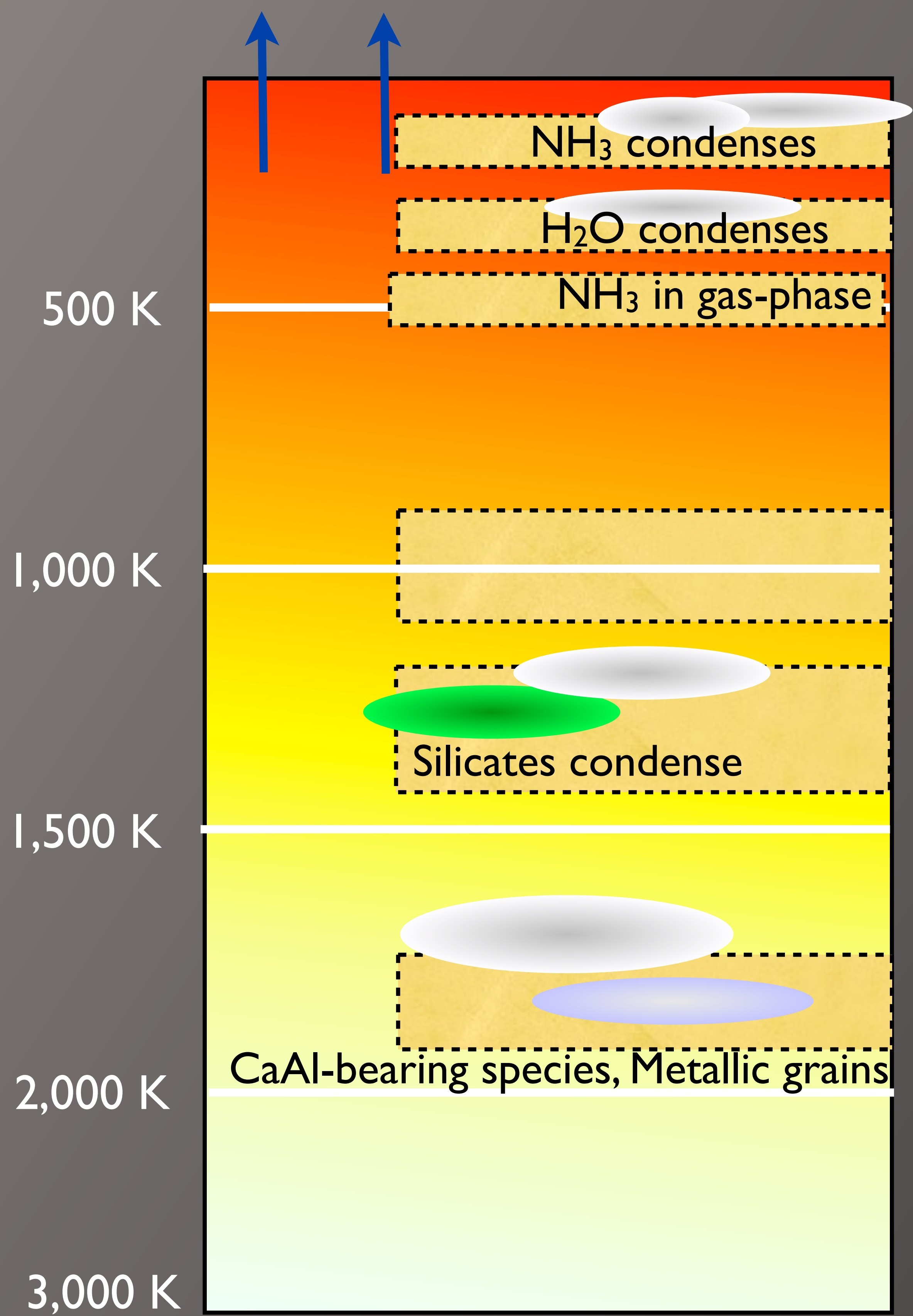


Hot Jupiters,
Some directly imaged planets
L-type BDs


500 K
1,000 K
1,500 K
2,000 K
3,000 K
Silicates condense
CaAl-bearing species, Metallic grains
T-dwarfs
Directly Imaged Planets
CH4 stable
CO


NH3 condenses
H2O condenses
NH3 in gas-phase
500 K
1,000 K
Silicates condense
1,500 K
CaAl-bearing species, Metallic grains
2,000 K
3,000 K
Y dwarfs
No such planet imaged/studied
CH4 stable
CO

Condensation and Cloud Formation



Determines Gas-phase Composition

Presence of Particles in the Atmosphere

↓

Fundamental Change in Opacities and Optical Depth

↓

Change P/T profile, Spectrum, Cooling efficiency

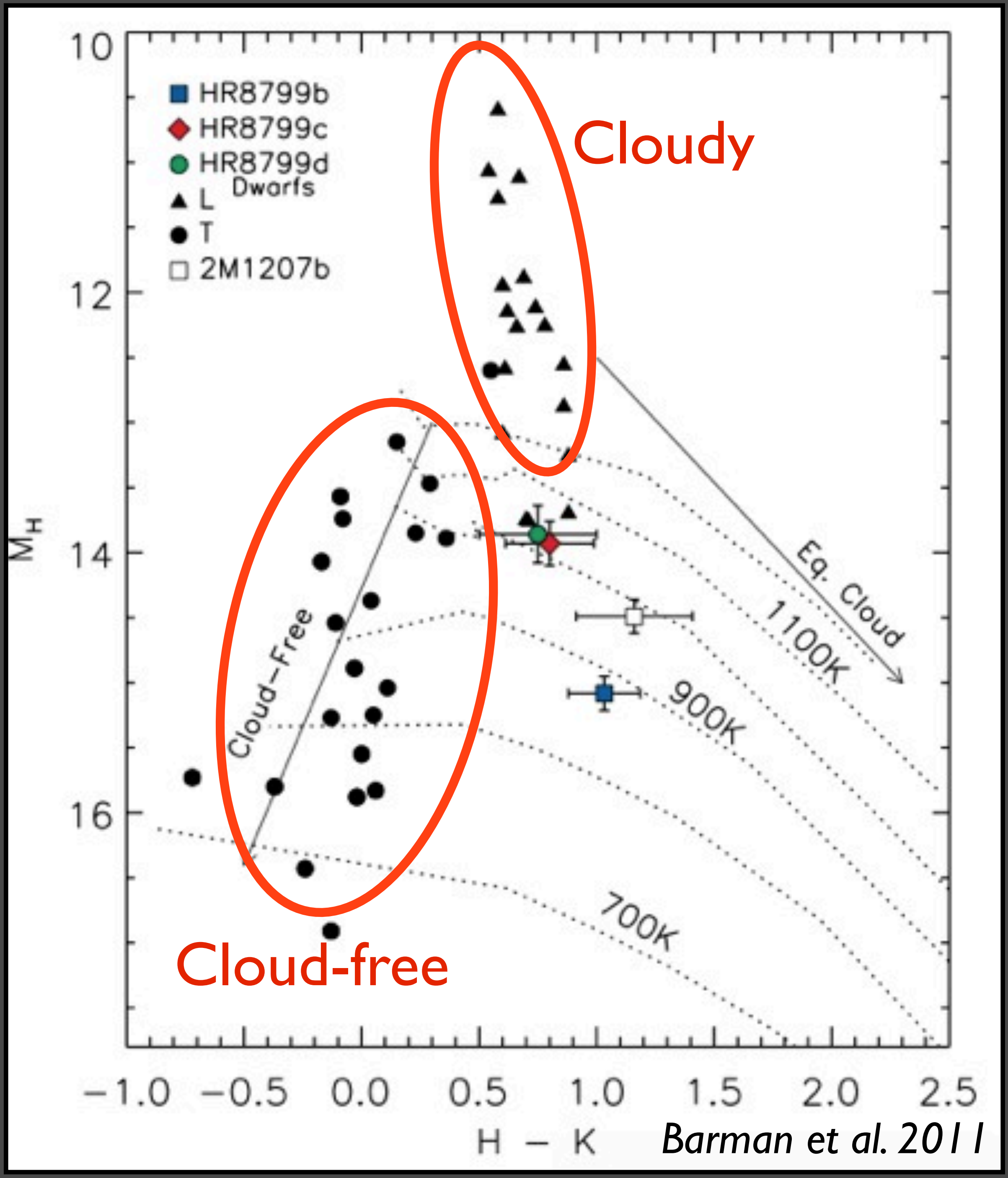
↓

Changes in the evolution and contraction speed

Marley et al. 2002, 2007 PPV, 2010;
Burrows et al. 2003, 2007, 2010, 2011;
Barman et al. 2011; Baraffe et al. 2003;

Cloud Formation and Structure

Many, different parameterization of vertical cloud structure, some ad hoc, none tested



Various Models and Ideas

Burgasser et al. 2002
Collapse of the Cloud layer / Patchy Clouds

Tsuji 2005:
Increasingly thinner, homogeneous cloud layer

Burrows et al. 2006: multi-condensate clouds

Marley, Saumon, Goldblatt 2011;
Barman et al. 2011

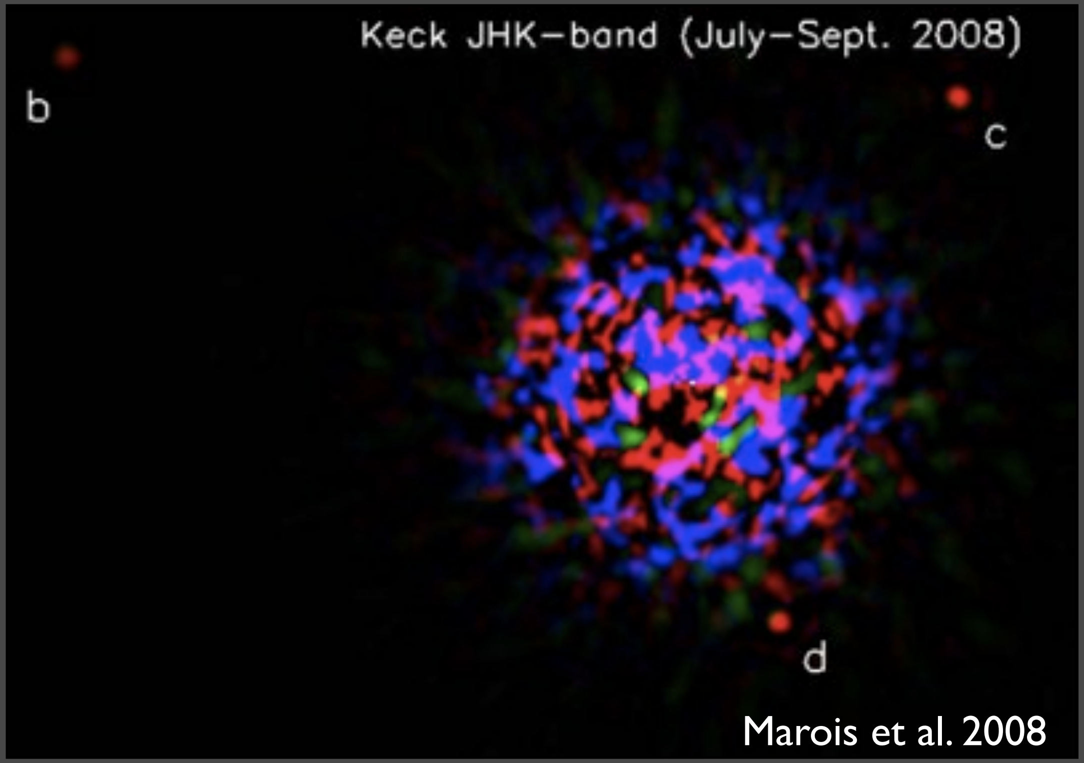
Patchy Clouds? Holes in Cloud Layer?

Questions:

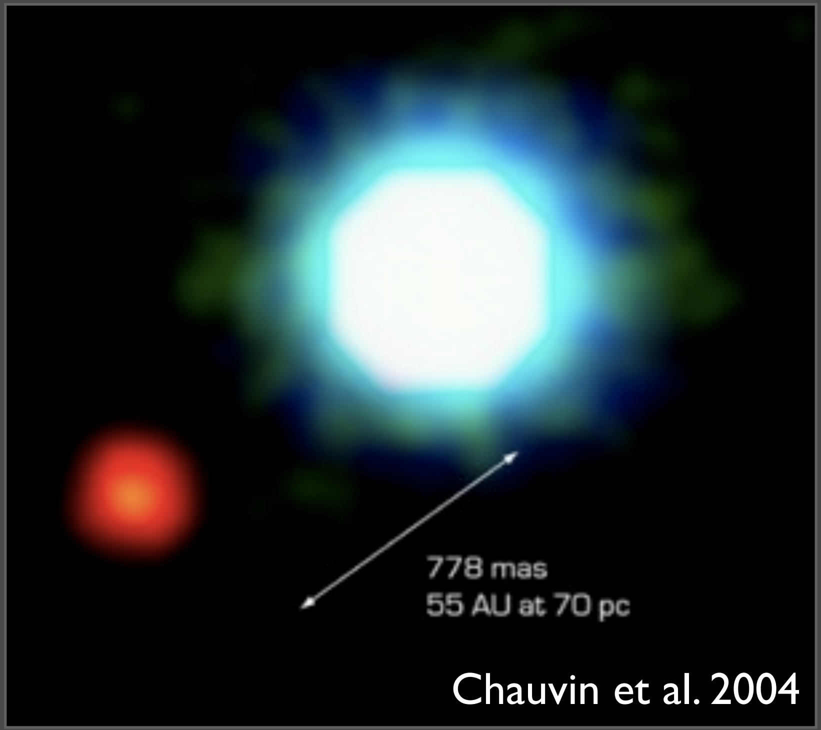
- What are the spectra, composition and physical structure of the clouds?
- What is the physical process leading to the L/T transition?

We need more than 1D Models

BUT: virtually no observational constraints



Marois et al. 2008

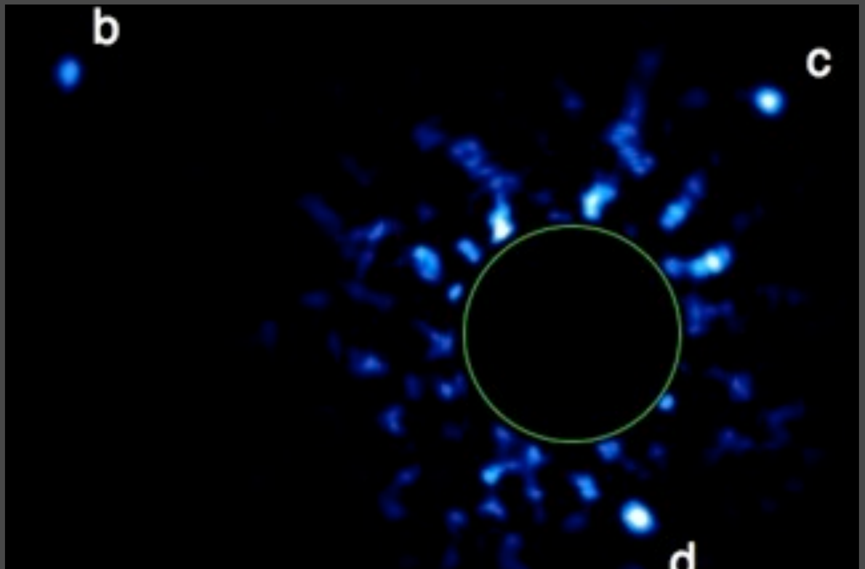


Chauvin et al. 2004

Phase Mapping


Jupiter / New Horizons


Mars / Viking



Apai et al. 2010

Cycle-18 HST Program with coordinated Spitzer Observations

PI: Apai
CoIs: Reid, Burrows, Radigan, Jayawardhana

WFC3 / G141 grism (~1.1 to 1.7 μm, R~120)
5 targets (3 with HST and 2 with Spitzer+HST)
What are the properties of the clouds?

Cycle-19 HST SNAP Program (60 orbits, PI: Apai)
Statistical approach on the importance of clouds in L/T dwarfs
How frequent are heterogenous cloud layers as function SpType?

Weather on Other Worlds
Spitzer Exploration Science Program (PI: Metchev, 840 hours)

Spitzer Large Program (PI: Radigan, 110 hours)

Cycle-18 HST Program with coordinated Spitzer Observations

Observations:

6 consecutive orbits on each target
Subarray mode of WFC3
R~120 wl=1.05-1.75 μm
No dithering
Every ~3-4 minutes a spectra with SN>200

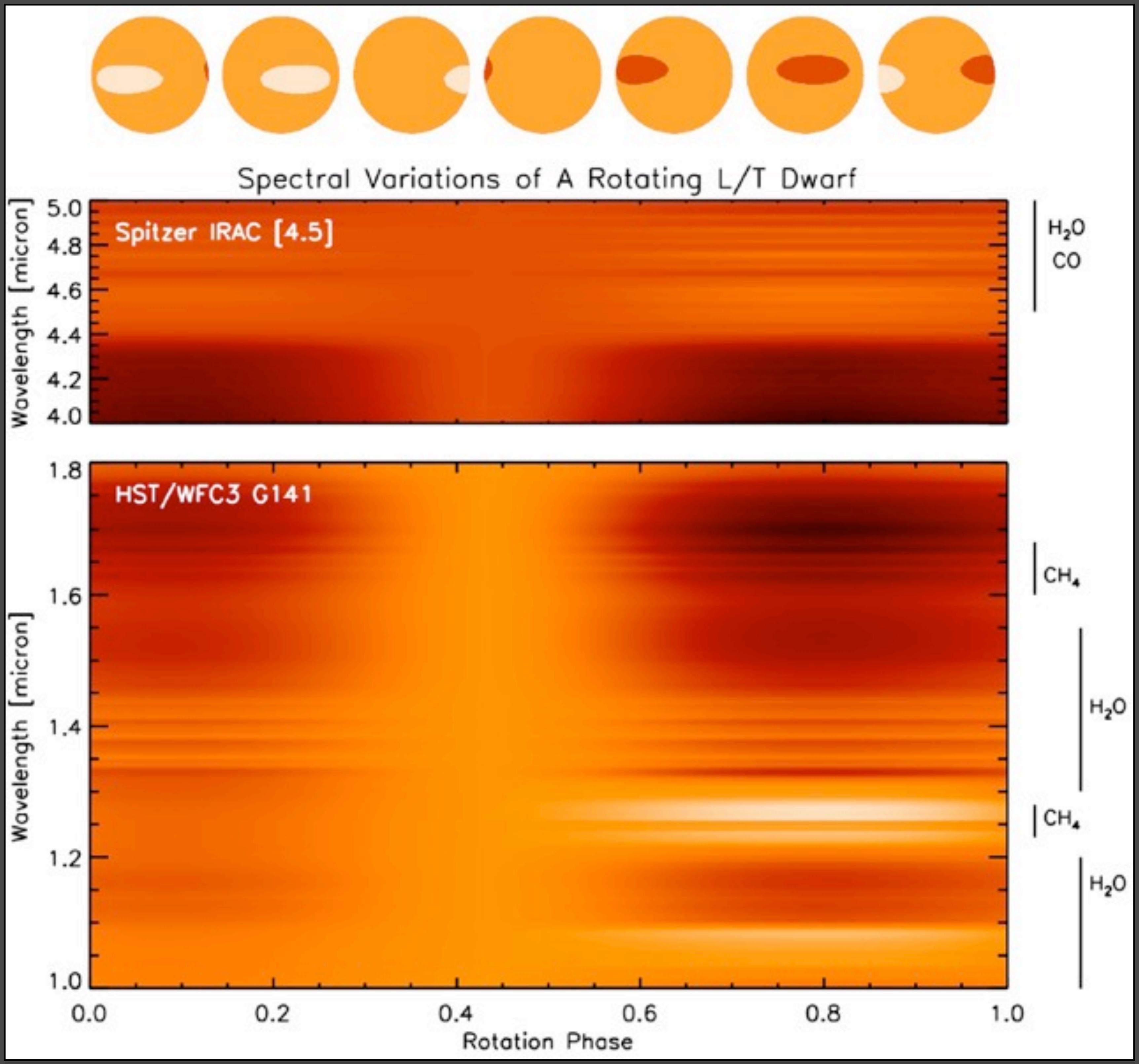
Reduction: pyraf/aXe and custom-made IDL scripts

Data on five targets:

L7 + L7 spatially resolved binary - no variability (<0.3%)
T2.5 BD - variability confirmed
T6 BD - variability confirmed
T2 - observations scheduled, known variable

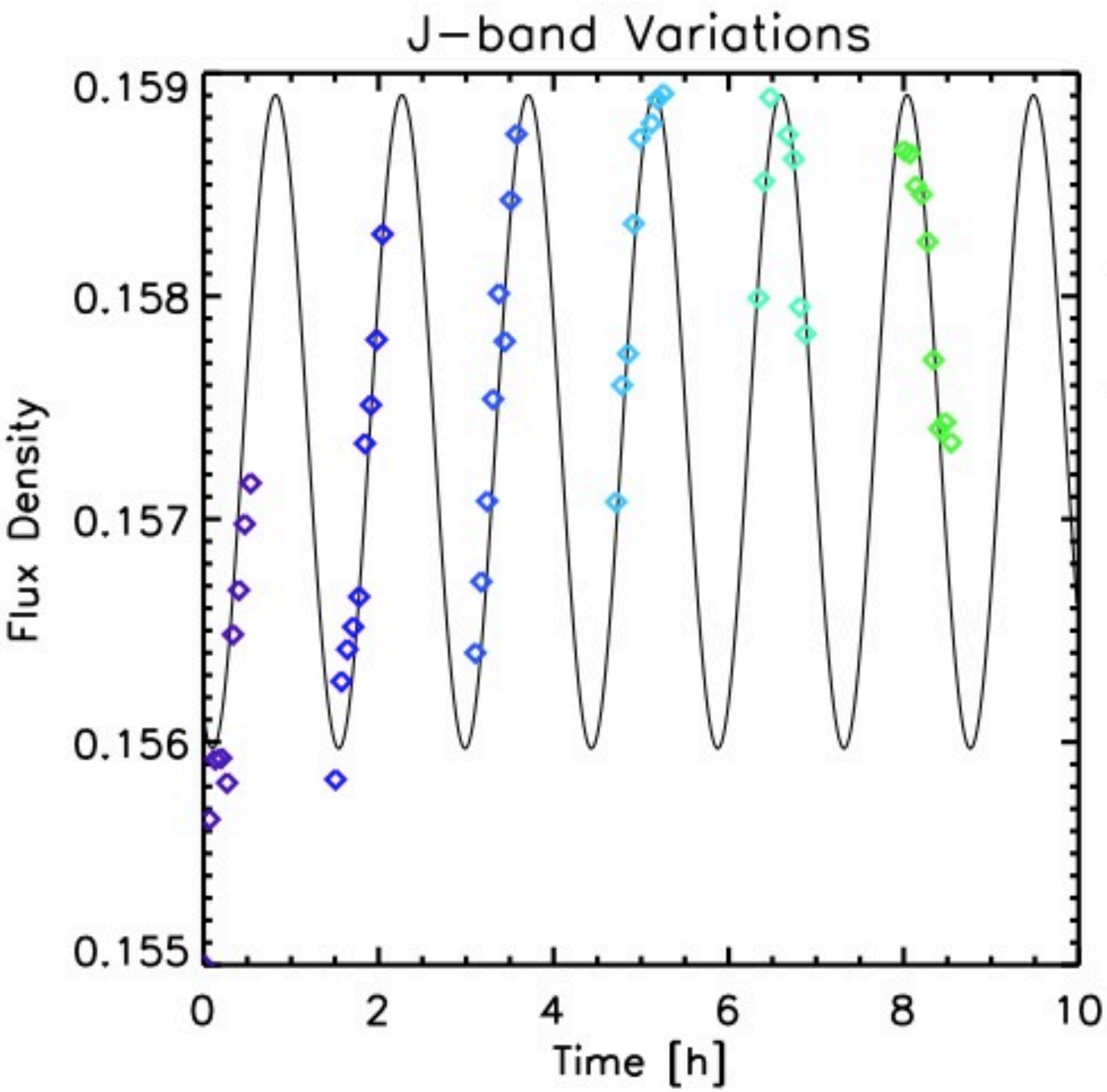
Two sources have coordinated/contemporary HST-Spitzer observations

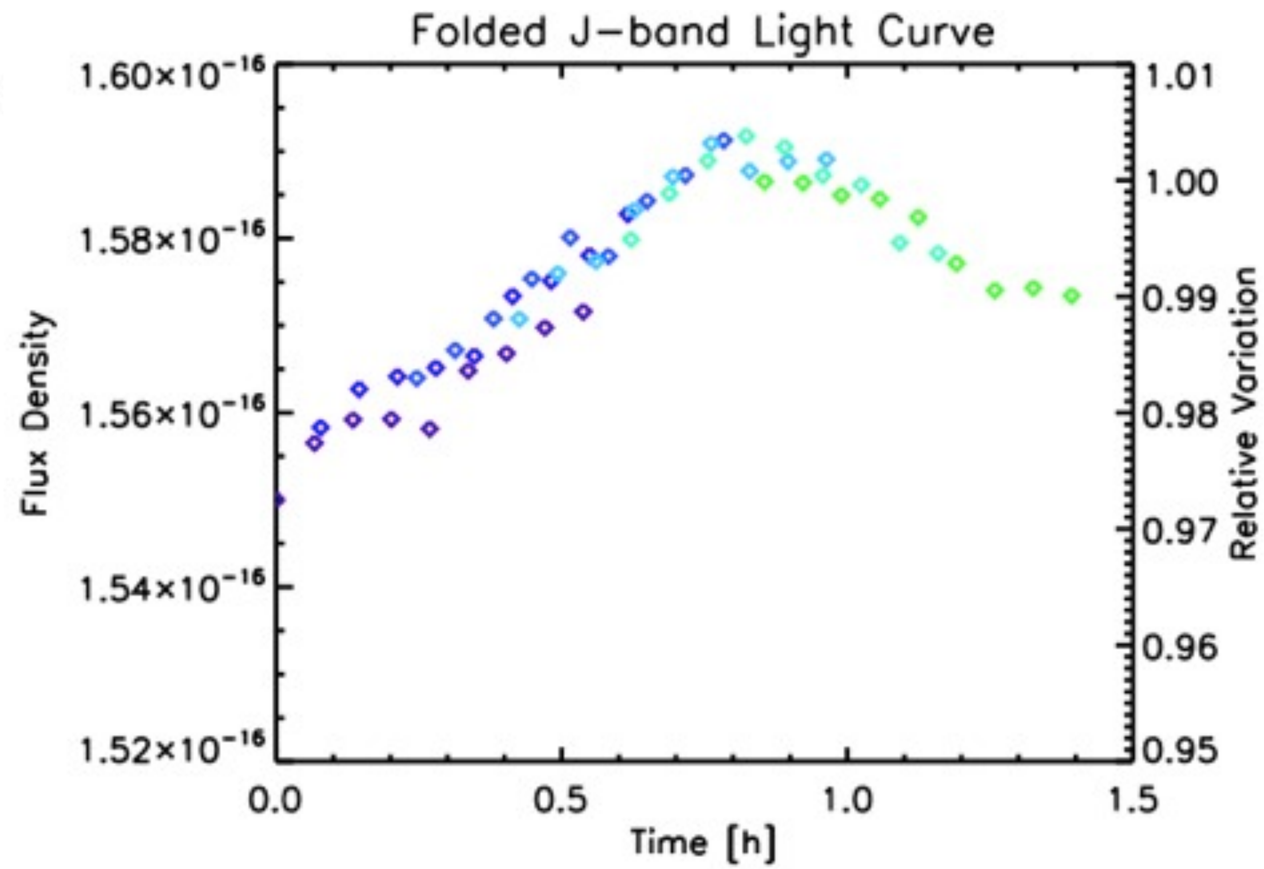
Mapping Brown Dwarfs

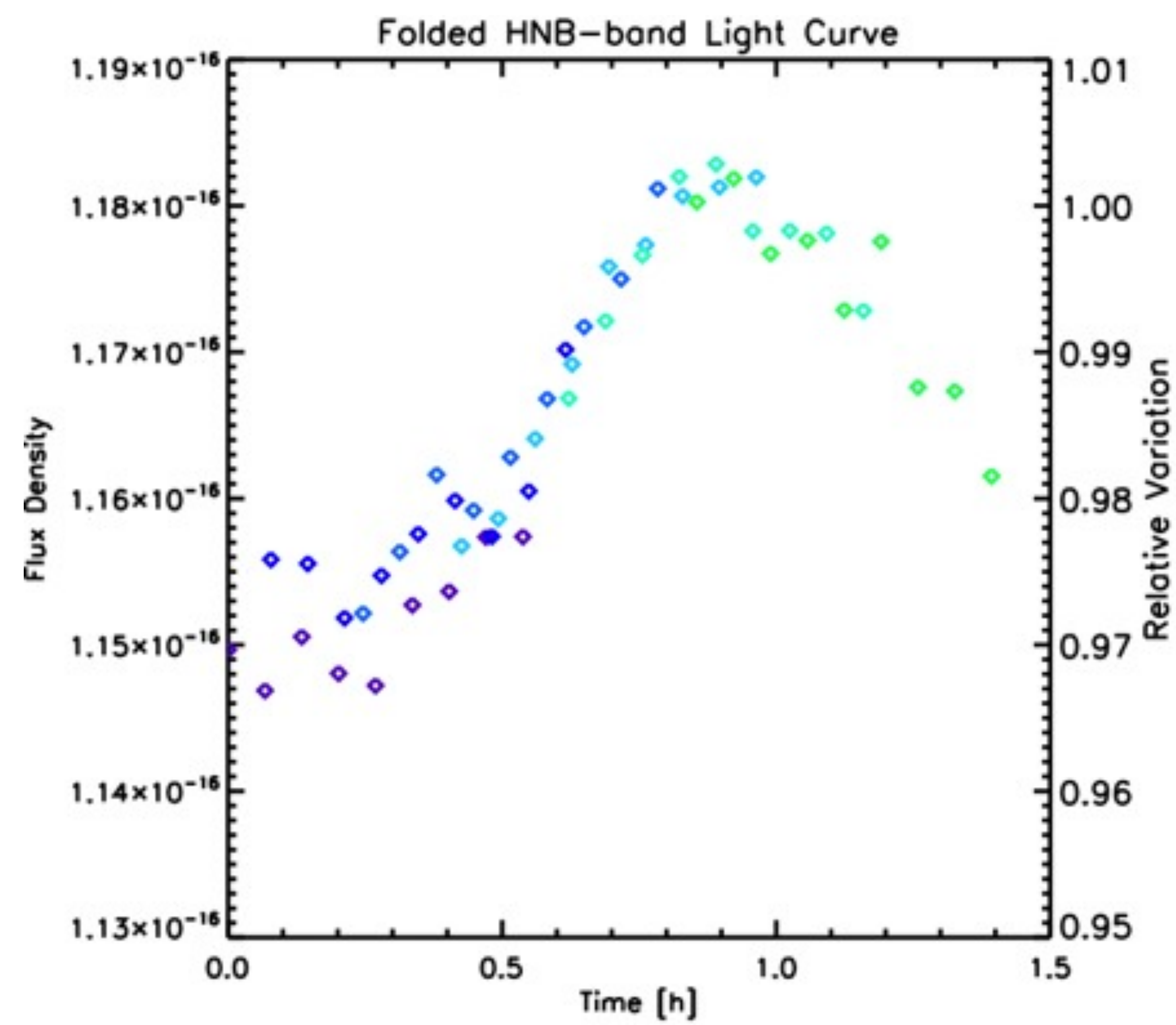


Similar Temperatures as HR8799bcd
Five targets: T, L/T, and L dwarfs

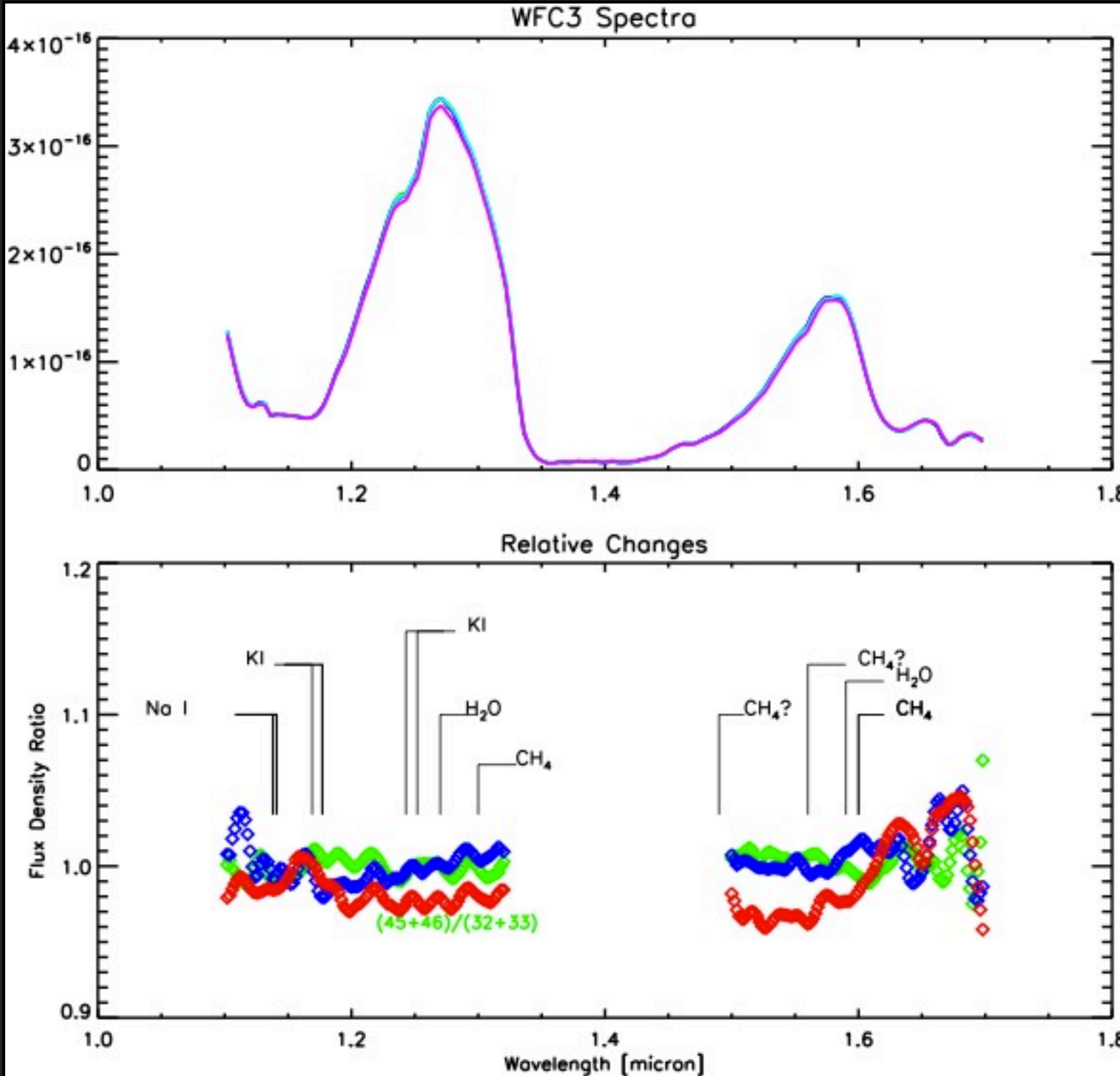
4-6% covering fraction with ΔT=350 K
10% covering fraction with ΔT=100 K

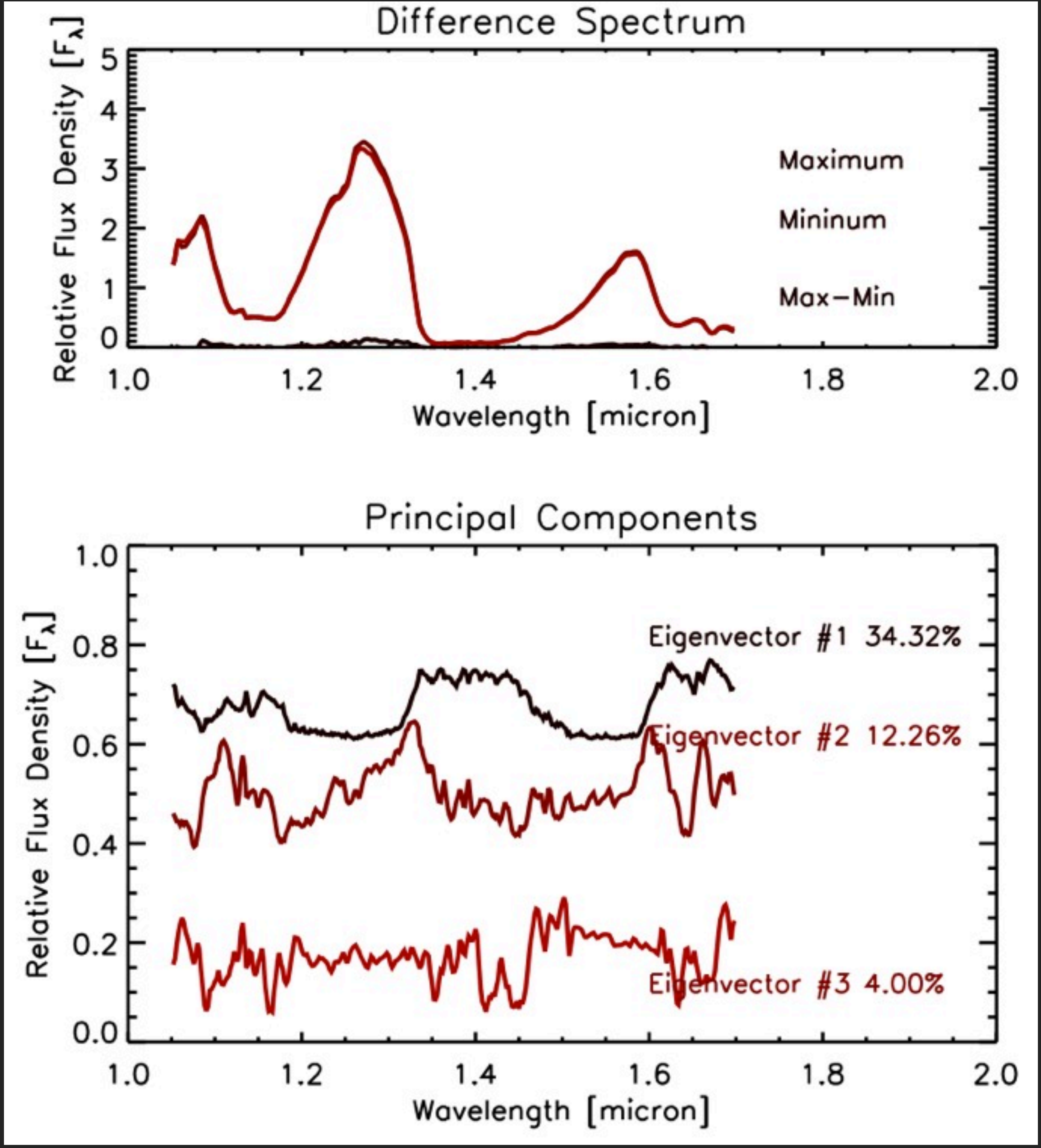


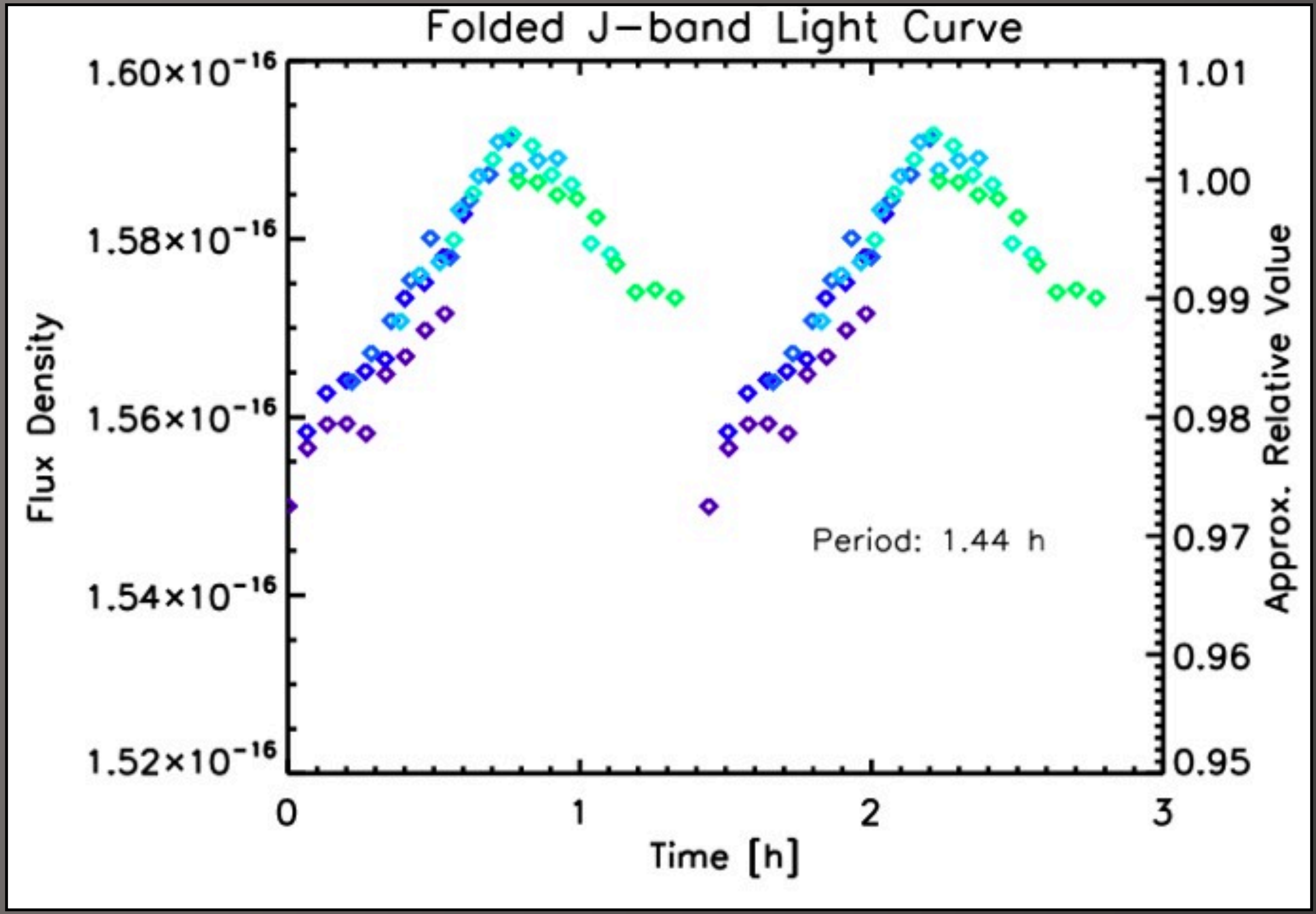




T6.5, J-Ks: 0.37 mag, H-K: 0.07 mag


WFC3 Spectra
4×10^{-16}
3×10^{-16}
2×10^{-16}
1×10^{-16}
0
1.0
1.2
1.4
1.6
1.8
Relative Changes
Flux Density Ratio
1.2
1.1
1.0
0.9
Na I
KI
KI
H_2O
CH_4
CH_4?
CH_4?
H_2O
CH_4
(45+46)/(32+33)
Wavelength [micron]

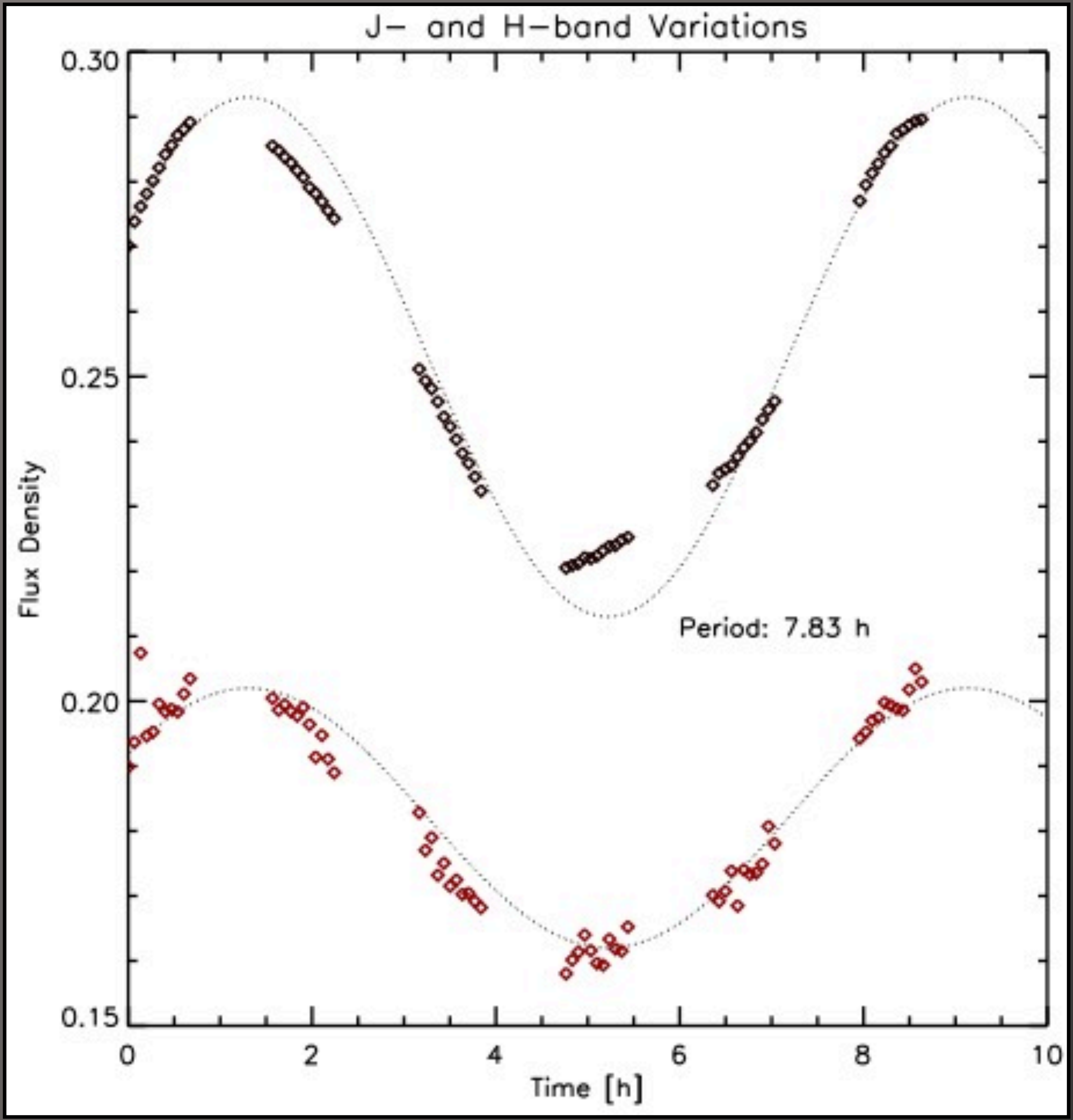

Difference Spectrum
Relative Flux Density [Fλ]
Maximum
Mininum
Max−Min
Wavelength [micron]
Principal Components
Relative Flux Density [Fλ]
Eigenvector #1 34.32%
Eigenvector #2 12.26%
Eigenvector #3 4.00%
Wavelength [micron]

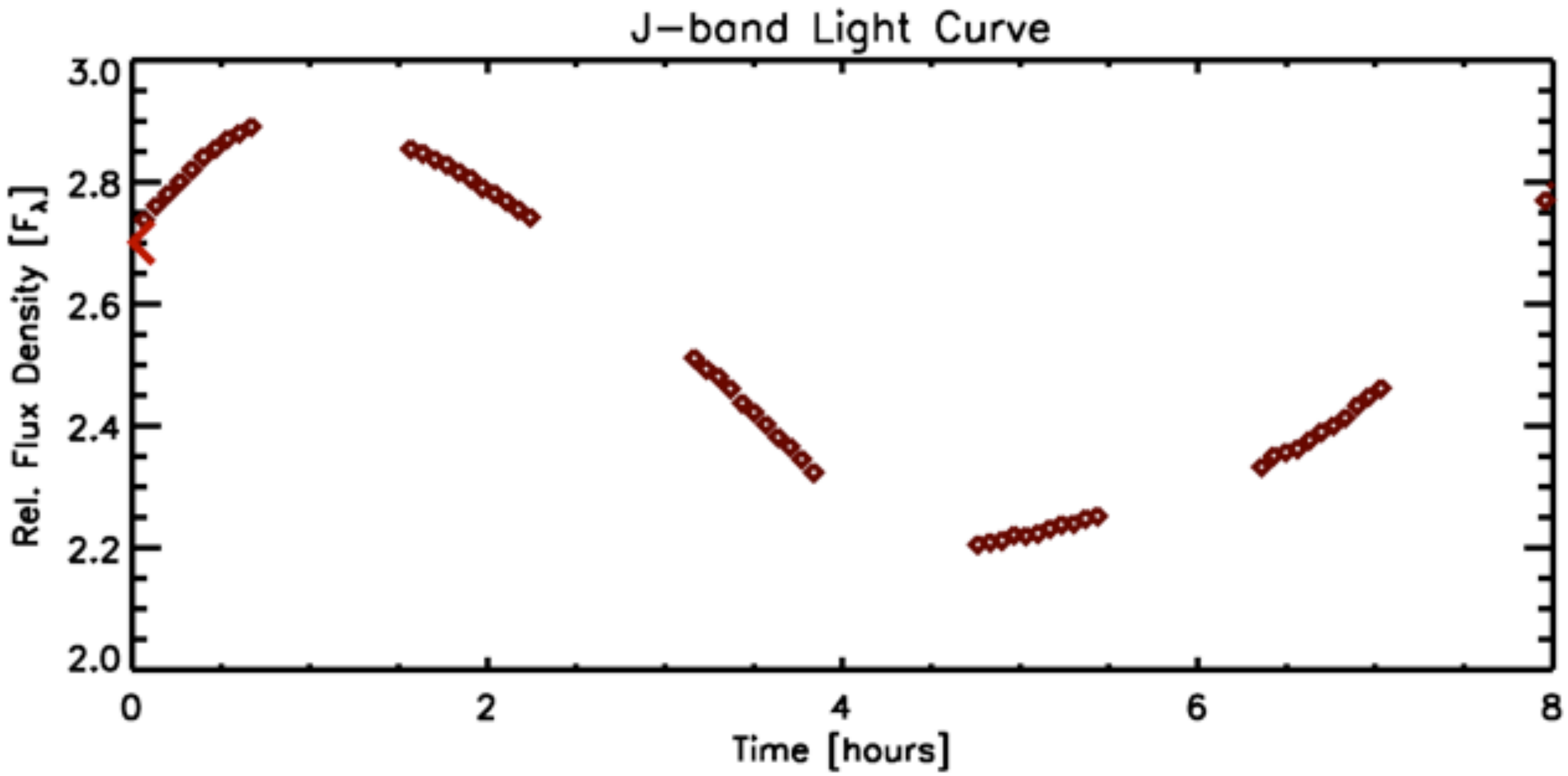


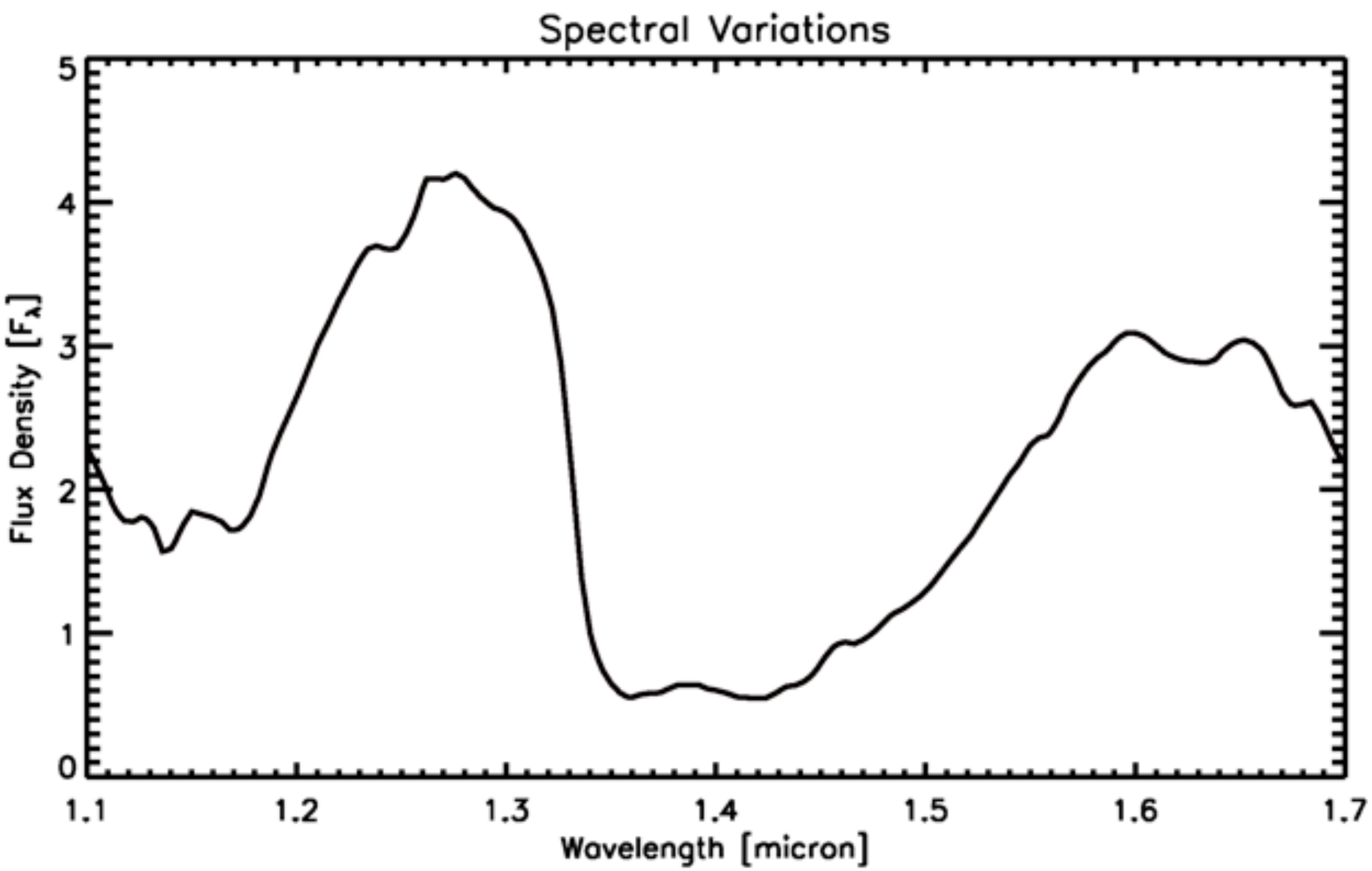
Combination of long-lived and short-lived features?
Possible "Storm"-like activity was reported for SIMP0136 (Artigau et al. 2010), indications in a few other objects (Gelino 2003)

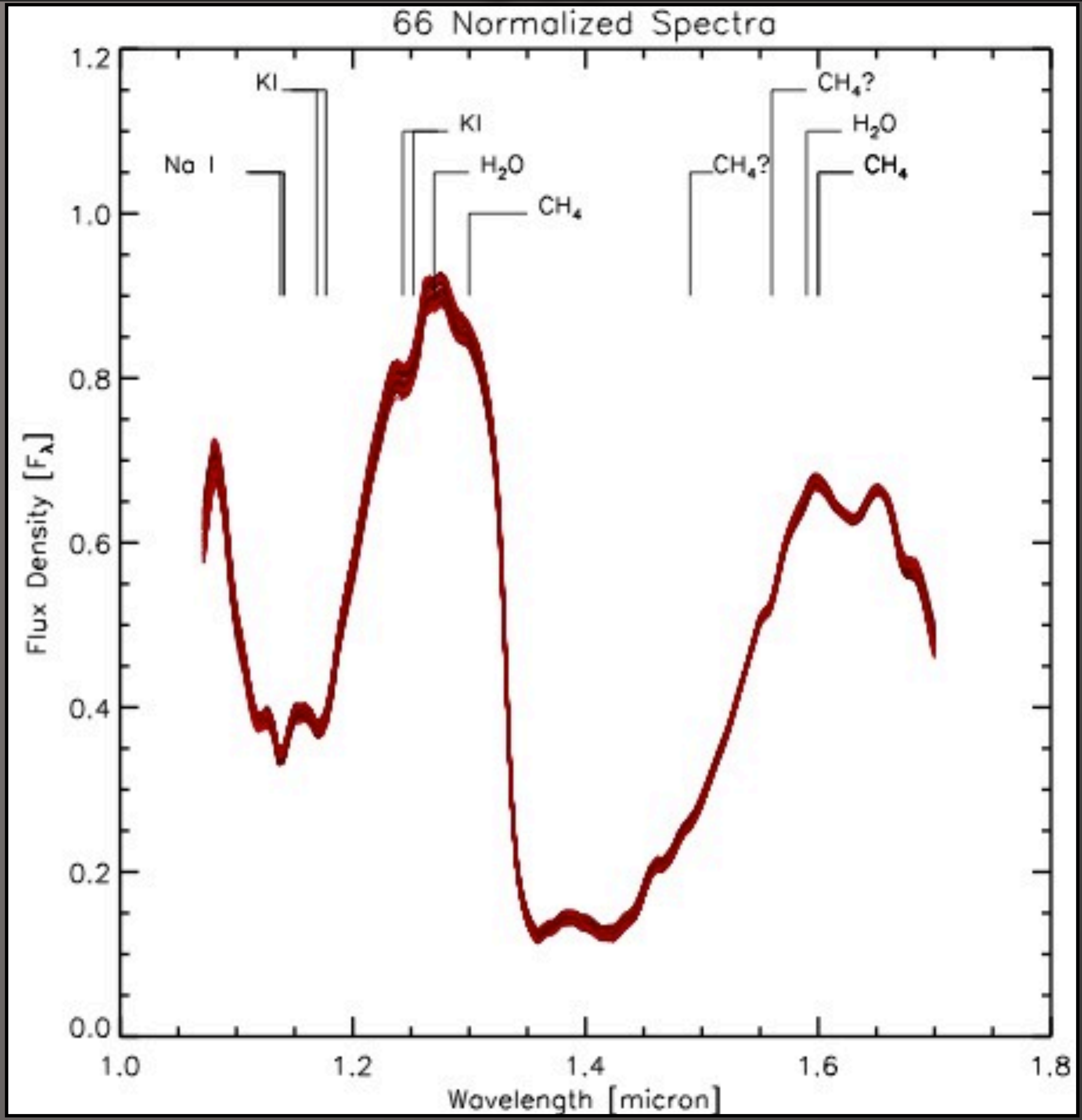
Source 2: J- and H-band flux density from HST spectra

T2 type, J-Ks: 1.68 mag, H-Ks: 0.58 - One of the best color and spectral matches to HR8799b

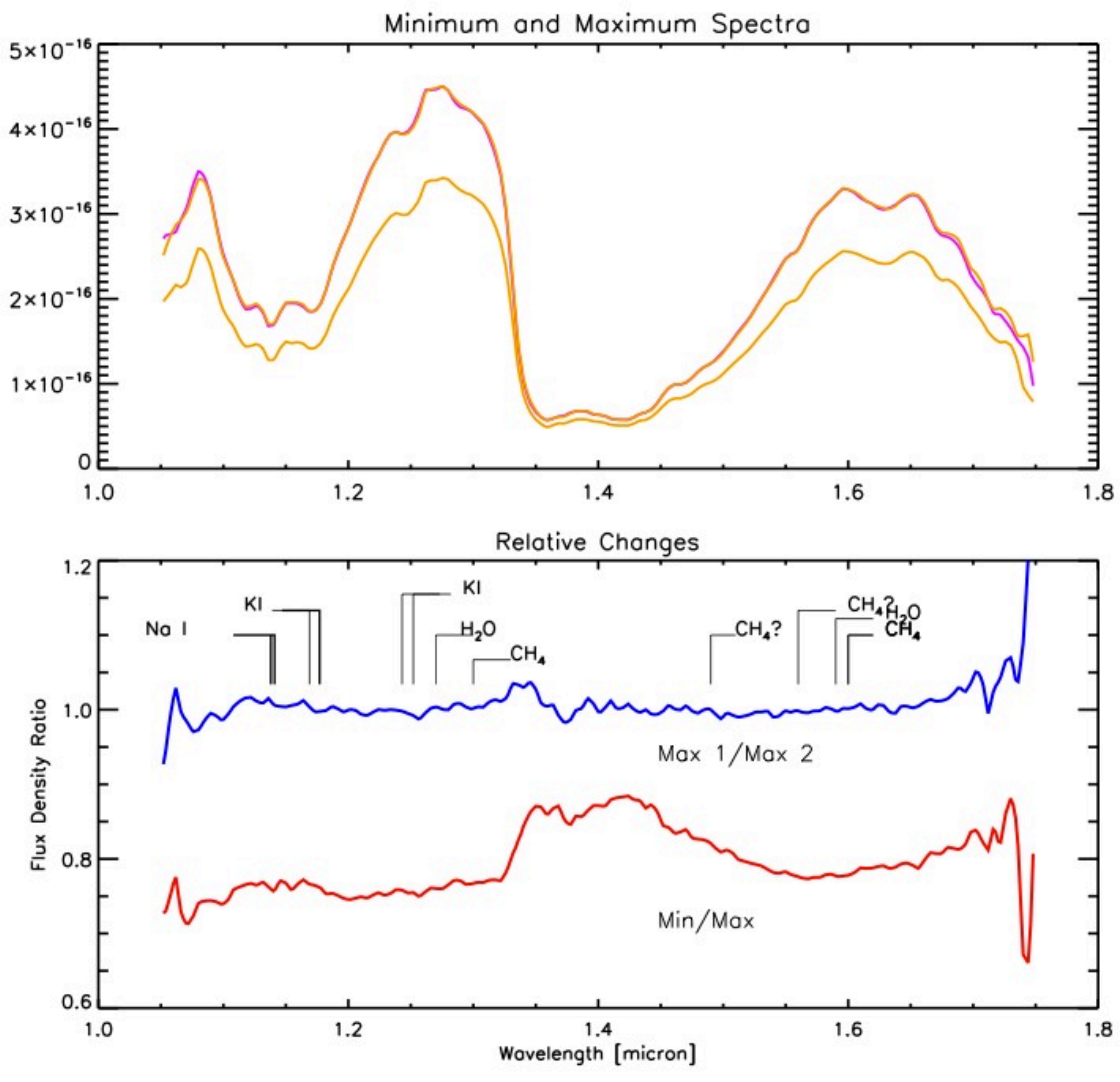


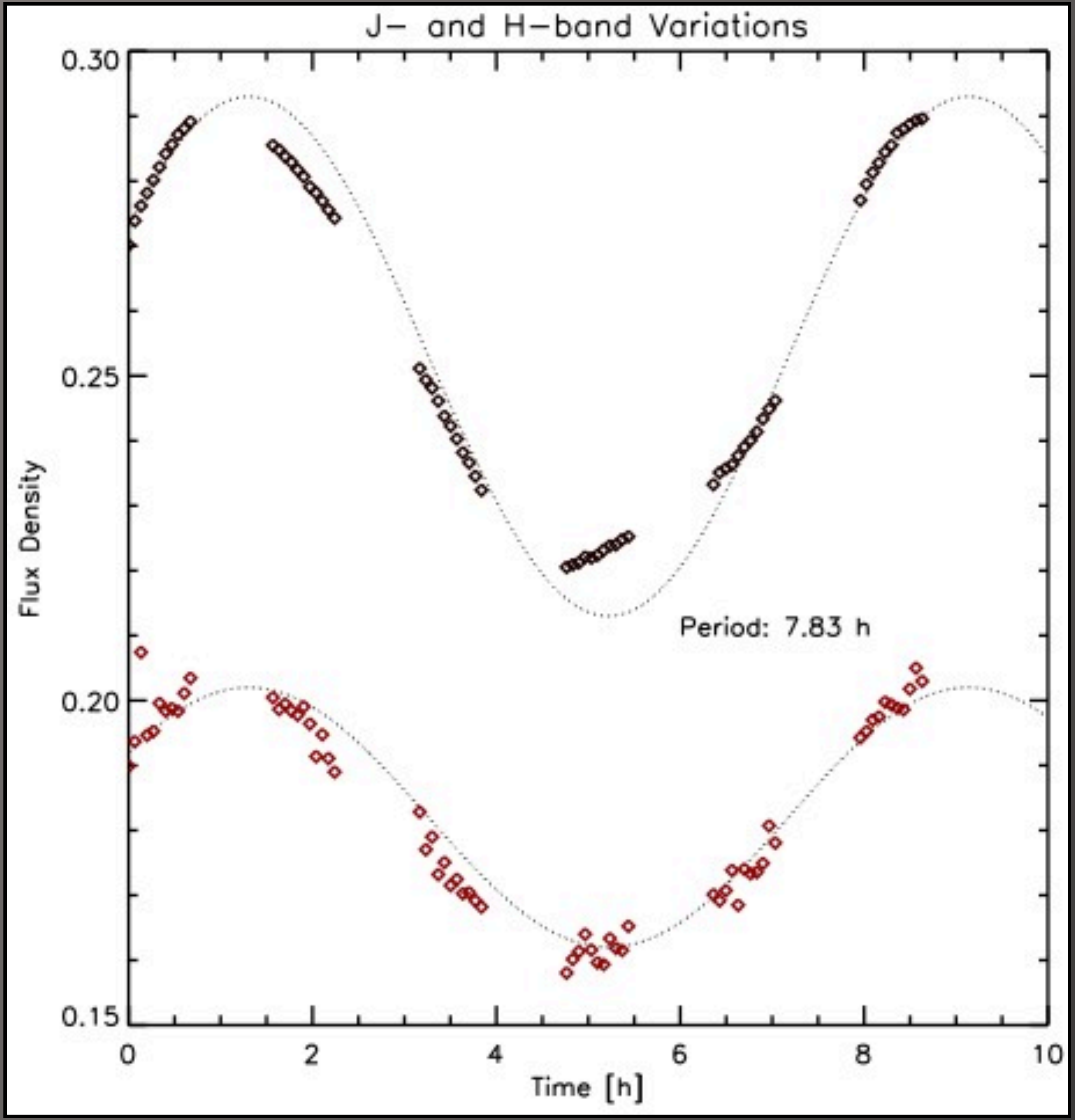

J–band Light Curve
Rel. Flux Density [F_λ]
3.0
2.8
2.6
2.4
2.2
2.0
0
2
4
6
8
Time [hours]


Spectral Variations
Flux Density [F_λ]
5
4
3
2
1
0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength [micron]

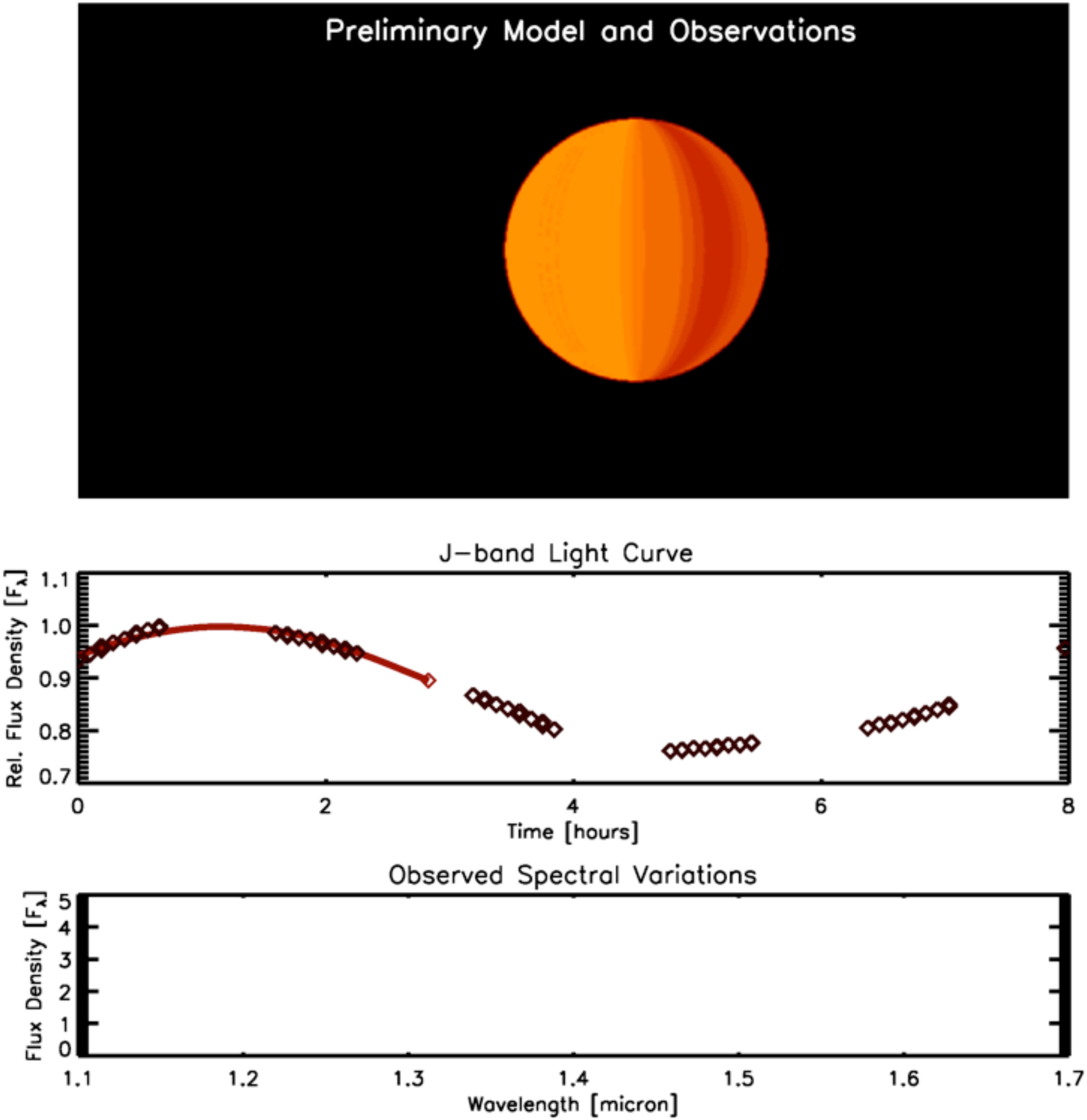


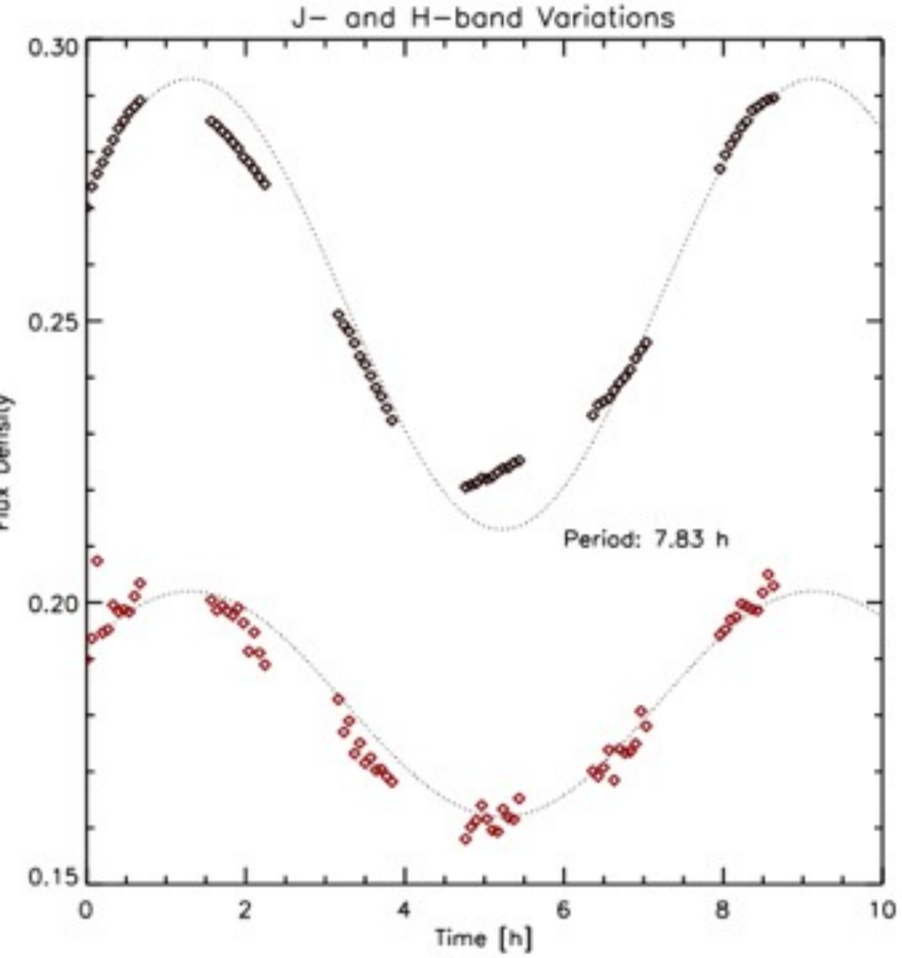
Resembles the case of 2M1207b: greatly underluminous wrt field spectral templates

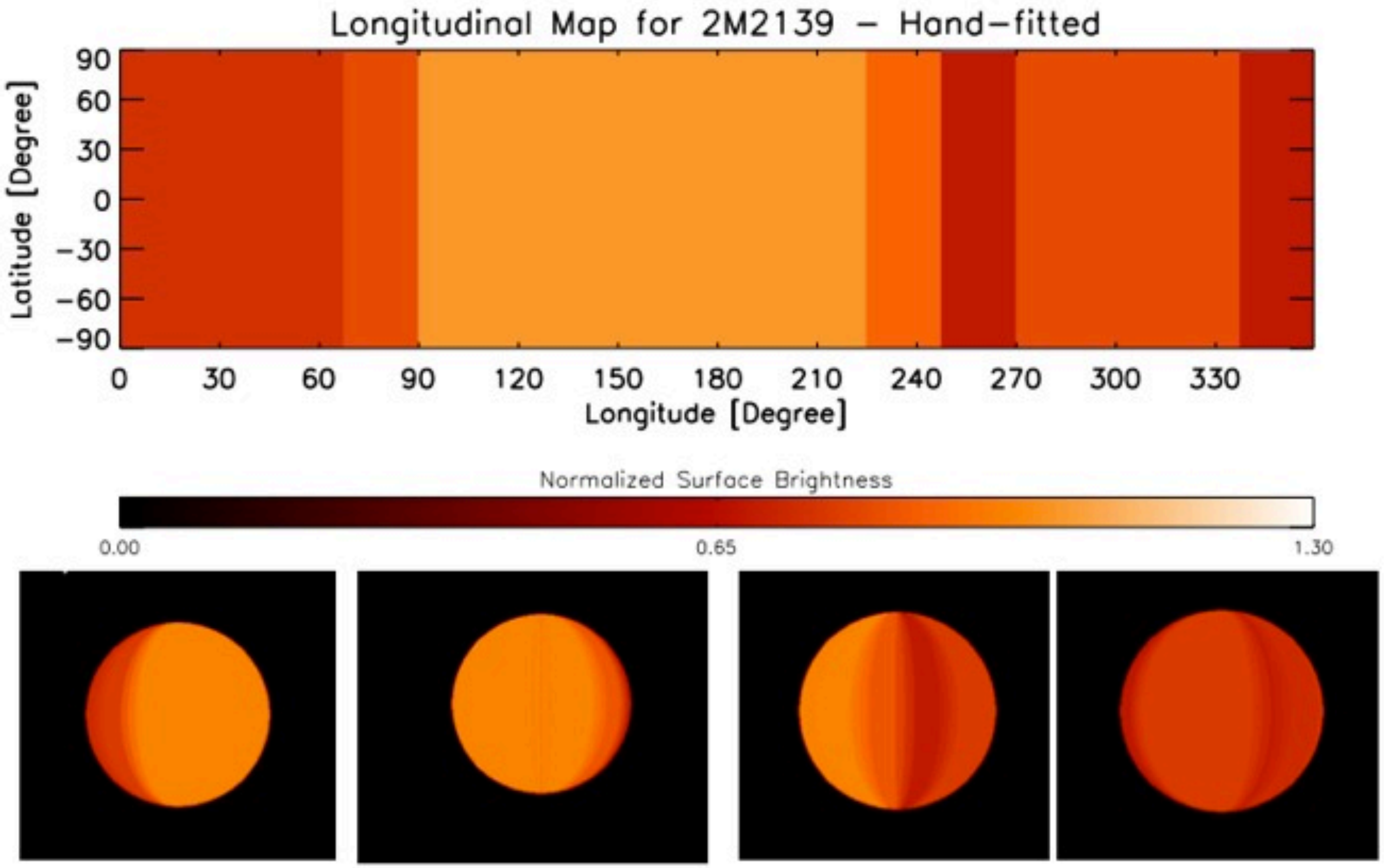

Minimum and Maximum Spectra
5×10^-16
4×10^-16
3×10^-16
2×10^-16
1×10^-16
0
1.0
1.2
1.4
1.6
1.8
Relative Changes
1.2
1.0
0.8
0.6
Flux Density Ratio
Na I
KI
KI
H2O
CH4
CH4?
CH4?
H2O
CH4
Max 1/Max 2
Min/Max
Wavelength [micron]



J- and H-band flux density from HST spectra


Preliminary Model and Observations
J–band Light Curve
Rel. Flux Density [F$_\lambda$]
1.1
1.0
0.9
0.8
0.7
0
2
4
6
8
Time [hours]
Observed Spectral Variations
Flux Density [F$_\lambda$]
5
4
3
2
1
0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength [micron]

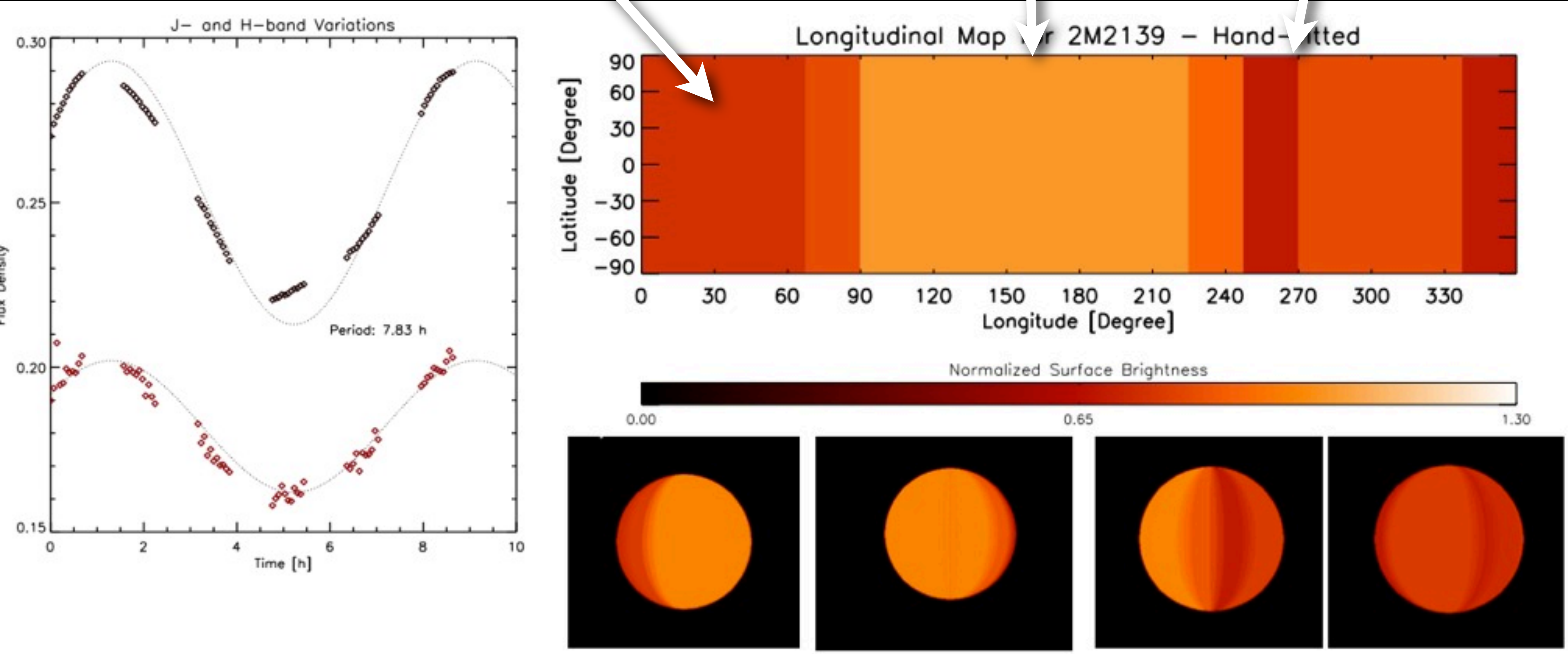

J– and H–band Variations
Period: 7.83 h
Time [h]
0.30
0.25
0.20
0.15
0
2
4
6
8
10


Longitudinal Map for 2M2139 – Hand–fitted
Latitude [Degree]
Longitude [Degree]
90
60
30
0
−30
−60
−90
0
30
60
90
120
150
180
210
240
270
300
330
Normalized Surface Brightness
0.00
0.65
1.30

Thicker cloud layer

Brighter hemisphere (hole in cloud layer)?

Darker patches



Source 1 (T6)

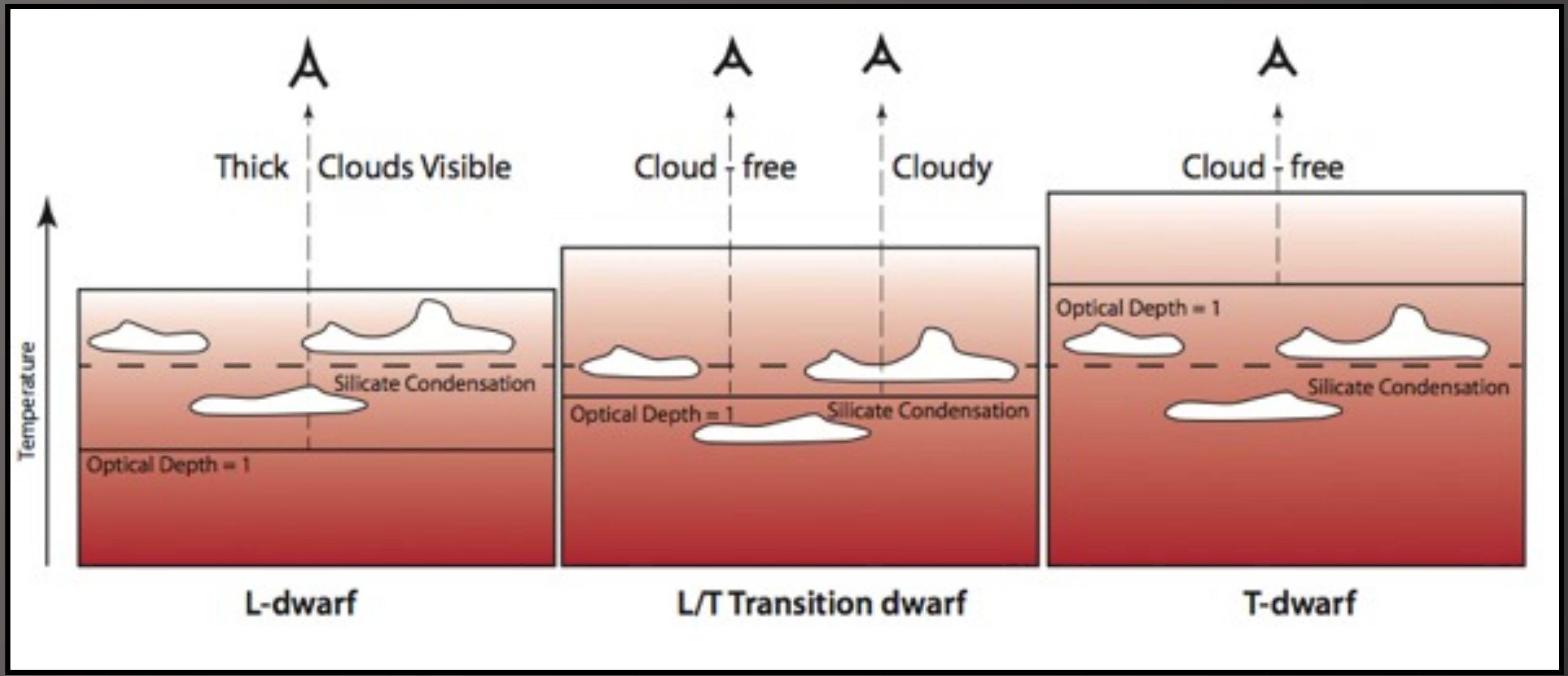
- Confirm periodic variations (P=1.44 h)
- Peak-to-peak amplitude 2%
- Preliminary PCA: two main spectral components

Source 2

- Confirm periodic variations, period (P=7.83 h)
- Peak-to-peak amplitude ~27%
- Preliminary PCA: one main spectral component

Both sources

- No evidence for variations in absorbers (CH_4, Na I, K I)
- Water absorption bands vary *less* than the rest of the spectra
- Overall LC shape is similar over 2-3 year timescales
- Some evidence for smaller-scale LC changes over few hours



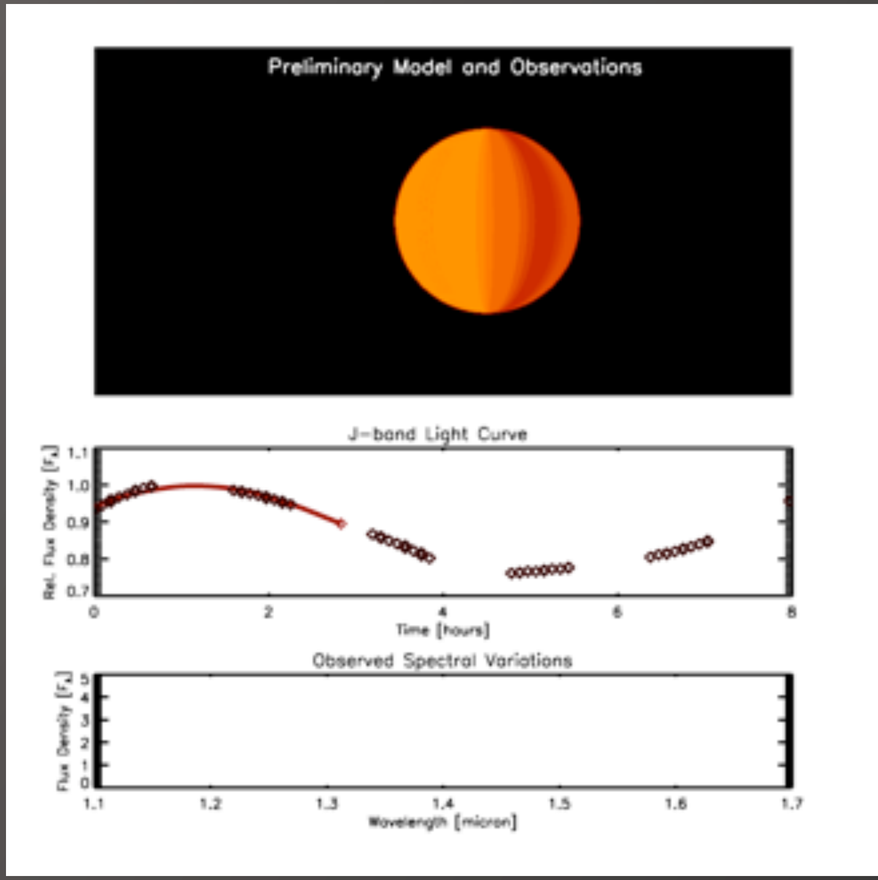
Ongoing Work

Inverting the Spectral Series
A genetic algorithm-based raytracer

61” + 2MASS simultaneous JHKs camera to monitor long-term evolution of the surface features

Cycle 19 HST Program: spectral variability survey of about 30 BDs

Ongoing Work



Inverting the Spectral Series
A genetic algorithm-based raytracer

61” + 2MASS simultaneous JHKs camera to monitor long-term evolution of the surface features

Cycle 19 HST Program: spectral variability survey of about 30 BDs

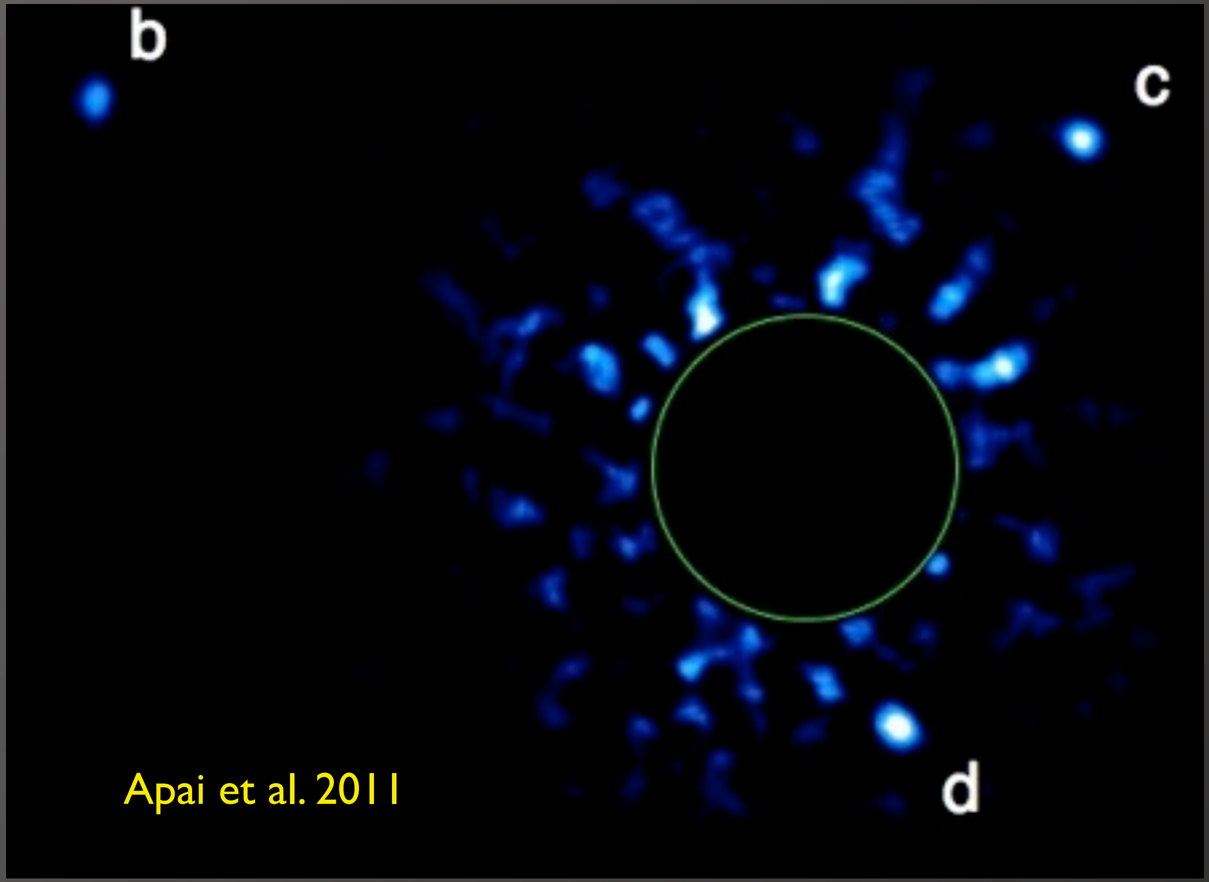
Relative Photometry in Directly Imaged Planetary Systems

Best match: partly cloudy, partly cloud-free model

BD with the largest amplitude variation known is close match

9 x 0.5 nights on VLT/NACO to pioneer this technique

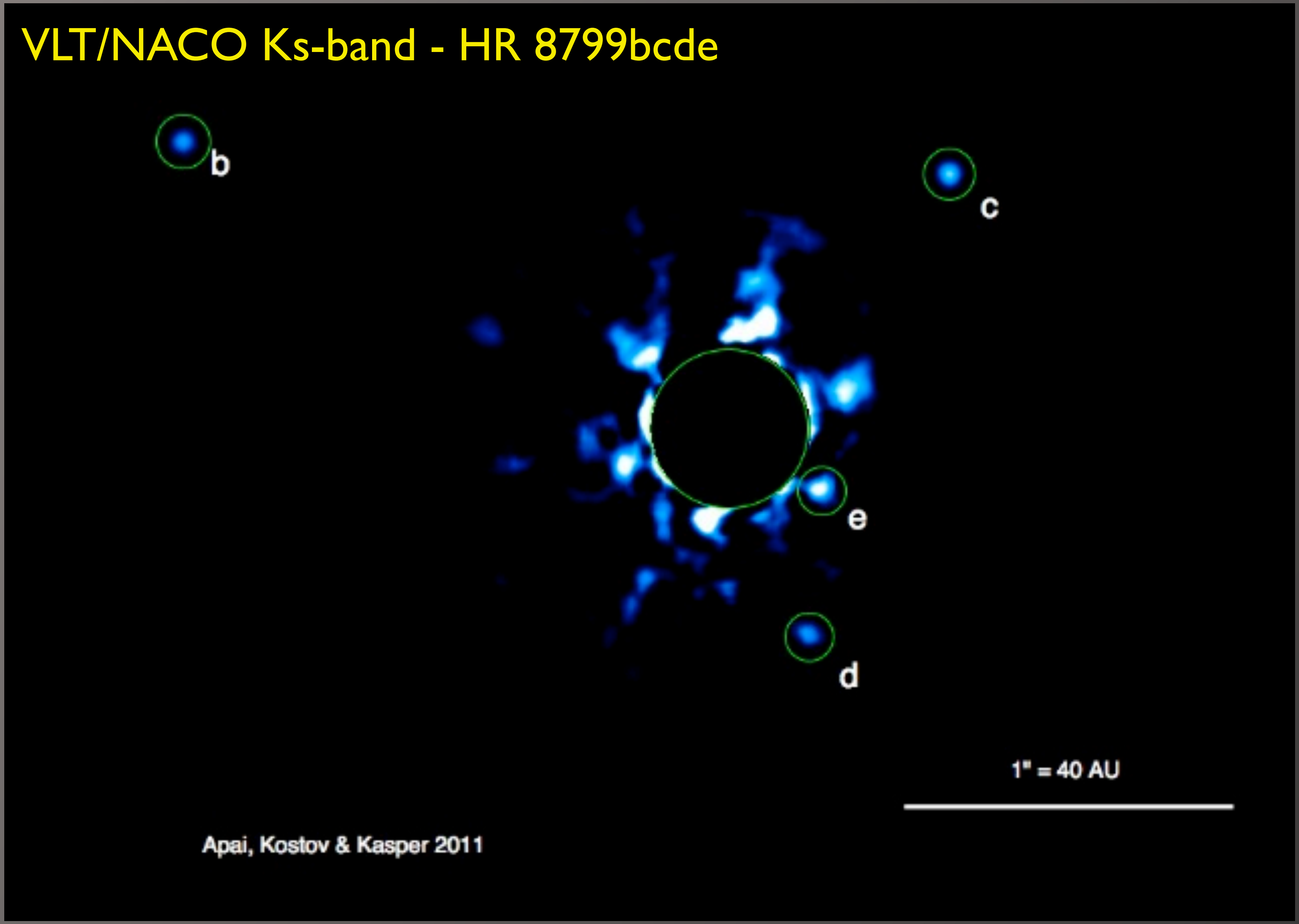
Light curves of Three Exoplanets



Apai et al. 2011

Goals:
1) Determine P_{rot} for planets
2) Estimate asymmetry in cloud cover

Fraction of the data published in Currie et al. 2011

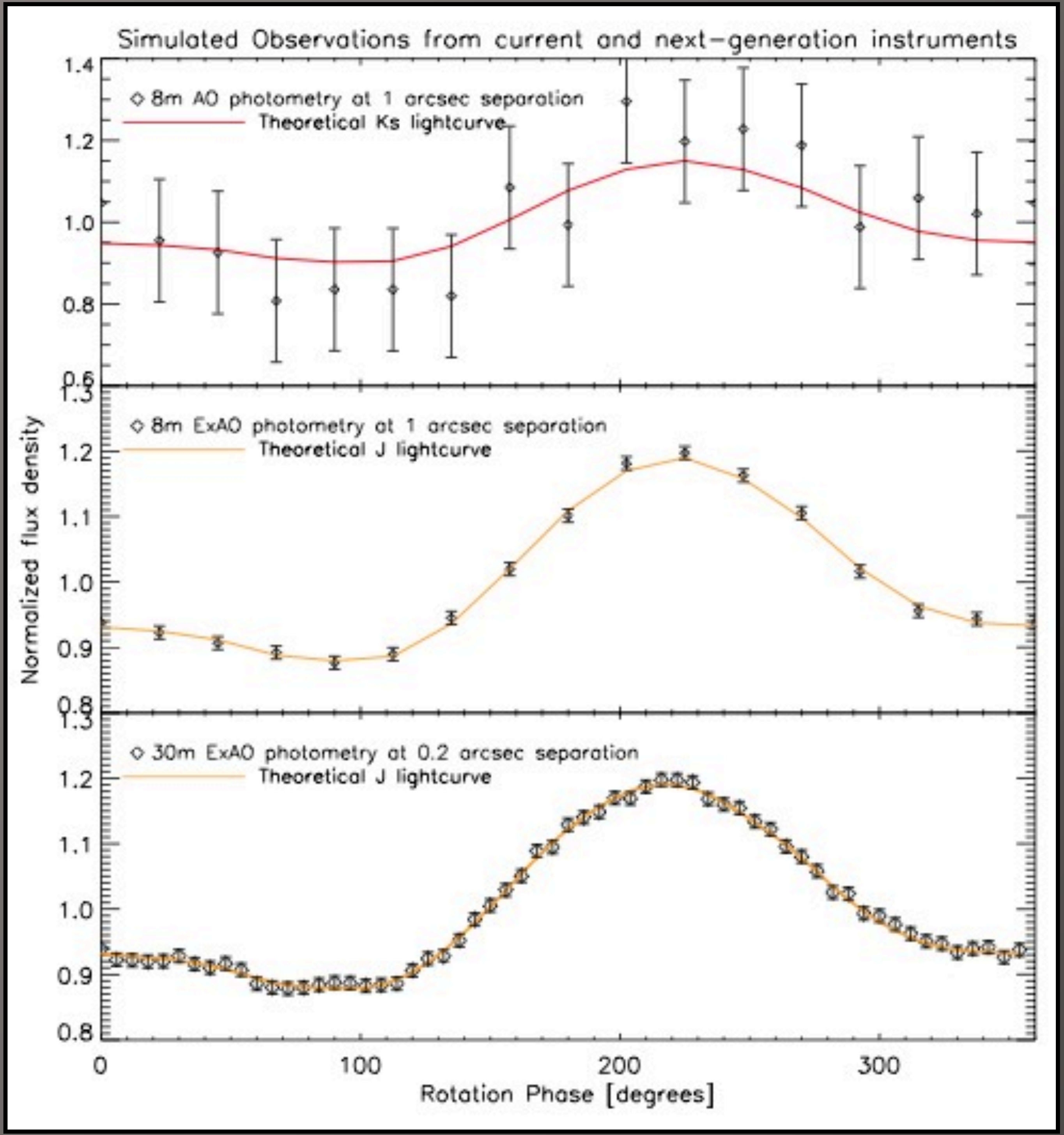


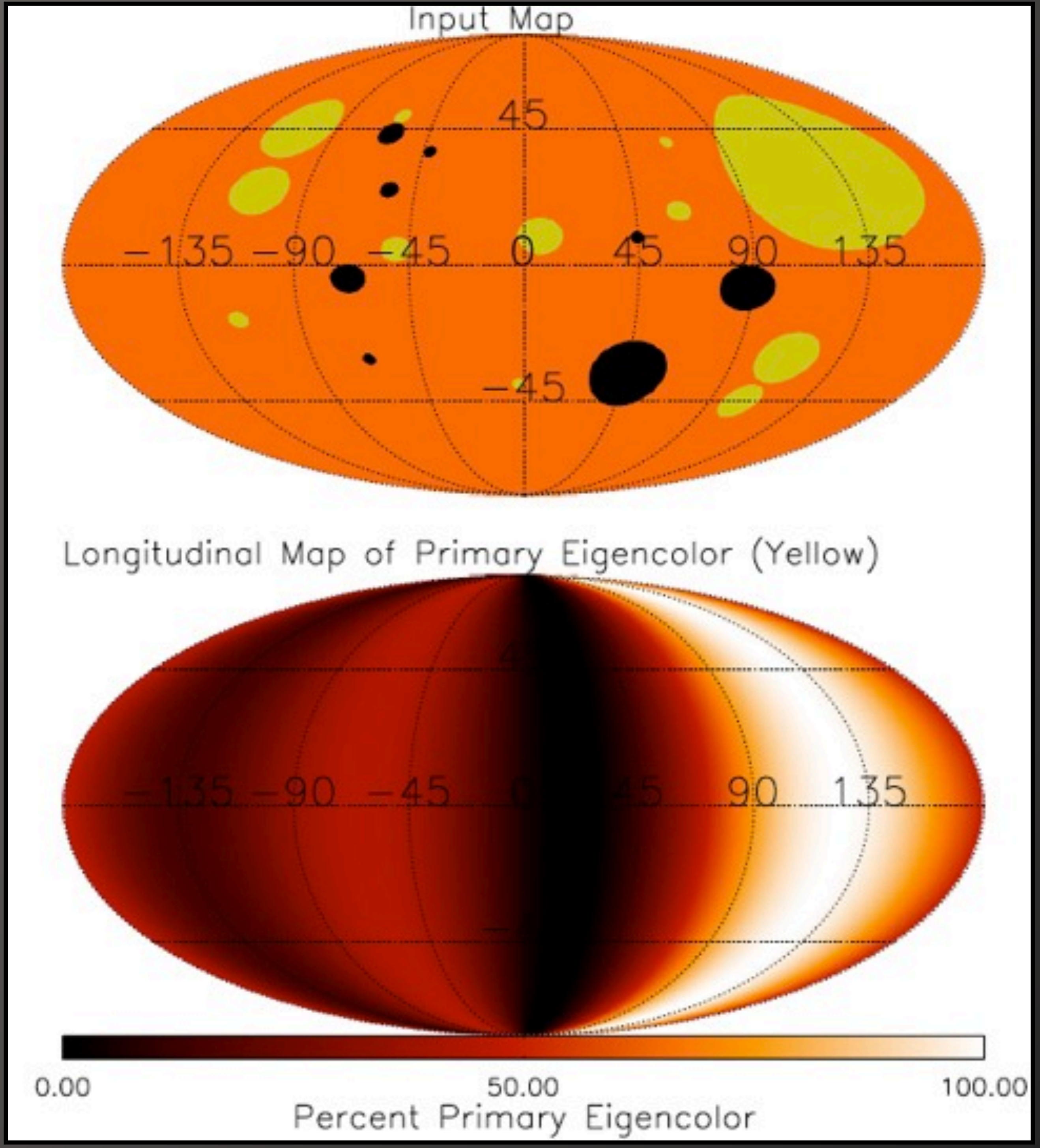
Angular differential imaging, but not LOCI

Future of Giant Exoplanet Phase Mapping

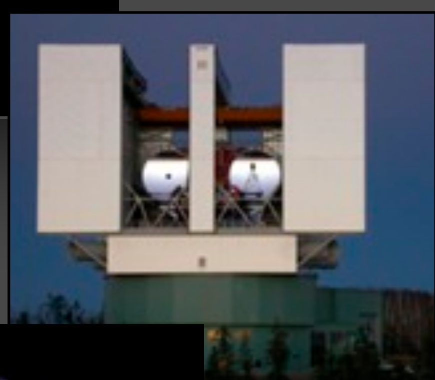
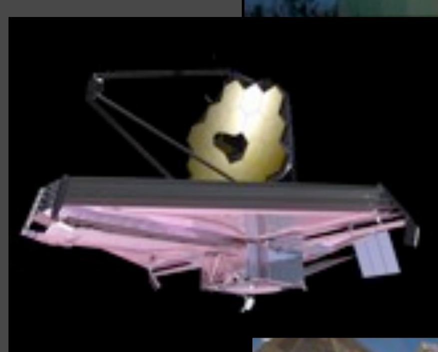
Discussion of the capabilities of future telescopes/instruments, ideal wavelengths/filters for observations, cadence, mapping techniques, limitations, etc.

Kostov & Apai 2012





Postcards from the Future


HST+Spitzer: (BDs) Spectroscopic variations

Spectrally resolved 1D map of clouds

Ground-based AO: Photometric variations

Rotation period

JWST/GMT: Spectroscopic/multi-color light curves

Spectrally resolved 1D map of clouds

Future Space Telescope: Exo-Earths

Spectrally resolved 2D map of planet and cloud cover

Summary

Clouds and Condensation are key to exoplanets/BD atmospheres

High Contrast Imaging: constrains giant planet population and directly detects giant planets

Several directly imaged planets may have thicker clouds than predicted

Techniques to Map Brown Dwarfs and Giant Exoplanets

HST Spectral + Spitzer Mapping
- Spectrally, spatially resolved maps
~5,300 points per target, sources much cooler than HJs
- Variations are broad-band with only slight wavelength-dependence
- Some LC evolution on ~10 h timescales, but general shape stable 2+ yr